• A NEW SERIES OF PLANT SCIENCE BOOKS •

edited by Frans Verdoorn

Volume XVIII

FOREST SOILS

and

FOREST GROWTH

"Thou gav'st me Nature as a kingdom grand,
With power to feel and to enjoy it. Thou
Not only cold, amazed acquaintance yield'st
But grantest, that in her profound breast
I gaze, as in the bosom of a friend.
The ranks of living creatures thou dost lead
Before me, teaching me to know my brothers
In air, water, and the silent wood."

GOETHE'S FAUST

FOREST SOILS

and

FOREST GROWTH

BY

S. A. WILDE, F.E., D.TECH.SC.

Associate Professor of Soils, University of Wisconsin;
Collaborator, Wisconsin Conservation Dept., and U. S. Forest Service;
formerly, Instructor in Forest Engineering, College of Technology, Prague

1946

WALTHAM, MASS., U.S.A.

Published by the Chronica Botanica Company

First published MCMXLVI
By the Chronica Botanica Company
of Waltham, Mass., U. S. A.

New York, N. Y.: G. E. STECHERT AND CO.,
31 East 10th Street.

San Francisco, Cal.: J. W. STACEY, INC.
244 Flood Building.

Ottawa, Ont.: THORBURN AND ABBOTT, LTD.,
115, Sparks Street.

México, D. F.: AXEL MORIEL SUCRS.,
San Juan de Letran 24-116; Ap. 2762.

Bogotá, and Medellín: LIBRERIA CENTRAL.

Lima: LIBRERIA INTERNACIONAL DEL PERU,
Casa Matriz. Boza 879; Casilla 1417.

Santiago de Chile: LIBRERIA ZAMORANO Y CAPERAN,
Compañia 1015 y 1019; Casilla 362.

Rio de Janeiro: LIVRARIA KOSMOS,
Rua do Rosario, 135-137; Caixa Postal 3481.

São Paulo: LIVRARIA CIVILIZAÇÃO BRASILEIRA,
Rua 15 de Novembro, 144.

Buenos Aires: ACME AGENCY, SOC. DE RESP. LTDA.,
Bartolomé Mitre 552.

London, W. 1: WM. DAWSON AND SONS, LTD.,
43, Weymouth Street.

London, W. C. 1: H. K. LEWIS AND CO., LTD.,
136, Gower Street.

Uppsala: LUNDEQUISTSKA BOKH.

Groningen: N. V. ERVEN P. NOORDHOFF.

Paris, VI: LIBRAIRIE H. LE SOUDIER,
174, Bvd. St. Germain.

Torino: ROSENBERG & SELLIER,
Via Andrea Doria 14.

Lisbon: LIVRARIA SÁ DA COSTA,
100-102, R. Garrett.

Moscow: MEZHDUNARODNAJA KNIGA,
Kuznetski Most 18.

Calcutta, Bombay, and Madras: MACMILLAN AND CO., LTD.

Johannesburg: CENTRAL NEWS AGENCY, LTD.,
Commissioner & Rissik Sts.; P. O. Box 1033.

Sydney: ANGUS AND ROBERTSON, LTD.,
89, Castlereagh Street.

Melbourne, C. 1: N. H. SEWARD, PTY., LTD.,
457, Bourke Street.

Made and printed in the U. S. A.

To Sec. 17, T. 39 N., R. 7 E., *4th* P. M.

THIS BOOK IS AFFECTIONATELY

DEDICATED

PREFACE

In the words of LIN YUTANG, *the outline of every tree "expresses a rhythm resulting from certain organic impulses: the impulse to grow and reach out toward the sunshine, the impulse to maintain its equilibrium, and the necessity of resisting the movement of the wind . . . . The result is something perfectly harmonious and immensely satisfying."*

The same law of organic impulses is indeed applicable to every aggregate of trees and shrubs, and other forms of life that are collectively called — forest. At the base of this natural coordination and harmony rests the soil, the medium that supports and nourishes different members of the forest community. The soil directly influences the composition of forest stands, their morphological pattern, rate of growth, quality of wood, reproductive vigor, degree of resistance to diseases, stability against the wind, and other important aspects. An understanding of the forest lies just as much below as above the ground line.

By virtue of its origin, the knowledge of forest soils incorporates findings made by foresters and soil scientists. It is natural, therefore, that any prospective author dealing with this subject is vulnerable to a dangerous temptation to merely select and arrange seemingly suitable fragments of information from pedology and silviculture. Unfortunately, many silvicultural conclusions have been drawn with little knowledge of the underlying soil; a good share of pedological observations has been made with no consideration of the botanical composition or productivity of the native vegetation. In this publication, I have sought to avoid these shortcomings and have aimed to interpret forest soils as carriers of definite floristic associations, as media for the growth of nursery stock or forest plantations, and as dynamic systems that react to different forms of silvicultural cutting. I also have made special effort to stress the importance of large genetic soil groups as natural acclimatizational units.

The first draft of this book originated from my lectures as prepared for a rather heterogenous group of students, including graduates and upper classmen in soils, forestry, botany, game management, and landscape architecture. This undoubtedly has resulted in a somewhat broad and unconventional treatment of the subject matter. As far as possible, generally accepted terminology has been used, but a number of deviations has been found to be necessary. Most of the material presented has been subjected to the test of field and laboratory trial, but the book is a pioneer effort in its field, and omissions are to be expected.

I have been influenced in my attitude by the works and personal instruction of the following teachers of soils and forestry: J. KOPECKY, G. F. MOROZOV, J. SIGMOND, JULIUS STOKLASA, EMIL TRUOG, G. N. WISSOTZKY, and A. R. WHITSON.

Dr. R. J. MUCKENHIRN *aided throughout in the preparation of the manuscript. Dr.* L. I. WILDE *rendered invaluable assistance in various phases of the work. A portion of the field and laboratory data incorporated in this book was accumulated in collaboration with* S. F. BURAN, H. M. GALLOWAY, J. G. CADY, STEPHAN KLIMAN, W. E. PATZER, D. P. WHITE, E. L. STONE, J. C. KOPITKE, C. J. KRUMM, OLGA NALBANDOV, R. O. ROSENDAHL, R. V. OLSON, *Dr.* L. H. SHINNERS, RUTH HARDY, *and* CATHERINE WATERS, *Assistants in Forest Soils, University of Wisconsin. Wholehearted cooperation in silvicultural investigations was extended by Messrs.* C. L. HARRINGTON, F. G. WILSON, F. B. TRENK, H. B. WALES, G. W. JONES, H. F. SCHOLZ, F. G. KILP, W. H. BRENER, *and* R. WITTENKAMP. *The entire outline or separate chapters have been criticized by Professor* D. M. MATTHEWS, *University of Michigan, Professor* E. J. GRAUL, *Dr.* A. J. RIKER, *Dr.* F. N. HAMERSTROM, *and* FRANCES HAMERSTROM, *University of Wisconsin, Dr.* H. R. ALDRICH, *Geological Society of America, Mr.* J. H. STOECKELER, *Lake States Forest Experiment Station, Dr.* W. W. UMBREIT, *Cornell University, and Dr.* P. R. GAST, *Harvard University. To all these I express my cordial thanks. Grateful acknowledgement is also made to Miss* MARGARET STITGEN, *Secretary of the Soils Department, who arranged the manuscript in its final form.*

The book was prepared for publication in the trying times of the war, and it owes its appearance to the perseverence of Dr. FRANS VERDOORN.

The support of the Wisconsin Conservation Department, the Wisconsin Alumni Research Foundation, and the U. S. Forest Service made possible the accumulation of a major part of the research data and field observations summarized in this volume.

THE AUTHOR.

Madison, Wisconsin

CONTENTS

LIST OF TEXT ILLUSTRATIONS

LIST OF TABLES

LIST OF PLATES

"Seeds upon the lands he scatters,
Seeds in every swamp and meadow,
Forest seeds upon the loose earth,
On the firm soil he plants acorns,
Spreads the spruce seeds on the mountains,
And the pine seeds on the hill-tops,
In the swamps he sows the birches,
On the quaking marshes alders,
And the basswood in the valleys,
In the moist earth sows the willows,
Mountain ash in virgin places,
On the banks of streams the hawthorn,
Junipers on knolls and highlands;
Thus his work did Pellerwoinen . . ."

THE KALEVALA, THE NATIONAL EPIC OF THE FINNS, DATED TO ABOUT 900 B. C.

Chapter I

HISTORICAL AND INTRODUCTORY

"De même qu'il y a une pédologie agricole, il existe une pédologie forestière."
HENRY, 1907

The Rise of Knowledge Relative to Forest Soils: — Forest soil is the medium that produces nature's most magnificent crop — an association of plants and animals distinguished by immense practical usefulness and by an infinite richness of patterns. Since time immemorial the daily needs and inborn inquisitiveness of mankind have stimulated interest in the soils of the forest. The early observations of the relationships that exist between the soil and forest vegetation were made by the primitive forest dwellers, hunters and medicine men. As science advanced, forest soils became a subject of systematic research. For more than a century, botanists, geologists, soil specialists, microbiologists, and silviculturists have been contributing to the knowledge of the edaphic factors of forest distribution and productivity. In recent years the information accumulated by students of forest soils has attained the form of a separate scientific discipline.

The early literature on soils and silviculture was marked by the appearance of a few noteworthy works published prior to 1800. The following list gives an outline picture of early writings:

1627 BACON, F. "Sylva Sylvarum"
1674 EVELYN, J. "Terra, a philosophical discourse of earth"
1713 CARLOVITZ, H. C. "Sylvicultura oeconomica"
1760 DUHAMEL, M. "Des semis et plantation des arbres, et leur culture"
1791 HARTIG, G. L. "Anweisung zur Holzzucht für Förster"
1795 DUNDONALD, THE EARL OF. "A treatise showing the intimate connection that subsists between agriculture and chemistry
1800 DARWIN, ERASMUS. "Phytologia, or the philosophy of agriculture and gardening"

Outstanding pioneer attempts to discuss soils in connection with silvicultural practices were made by H. COTTA (1809), HUNDESHAGEN (1830), SPRENGEL (1831), and SCHANTZ (1832). The texts of both latter authors bore the title of "Chemistry for agriculturists, foresters, and assessors."

In 1840 the principles of soil science and ecology were introduced to silviculture by GREBE, a German forester. His doctor's thesis "De conditionibus ad arborum nostrarum saluentium vitam necessariis," submitted at the University of Marburg, may well be considered as the cornerstone of forest soil science. The "Forstliches Cotta Album," published in 1844, includes the following statement of GREBE, remarkable for its vision: "As silvicultural horizons widen, the importance of environmental conditions becomes more sharply pronounced. It appears clearly to the foresters that the form of forest management is determined by a number of physical influences related to topography, geology, type of soil and climate."

A text on forest soils published by GREBE in 1852 was followed by similar works of B. COTTA (1852), HEYER (1860), and GIRARD (1868). In 1860, PFEIL, a German authority on forest management, published a book with an extensive chapter devoted specifically to the conditions of environment and entitled "Science of Forest Habitat." The variation in the results of the same silvicultural operations obtained under different conditions of climate and soils led PFEIL to introduce his paradox: "The only general rule in forestry is that there are no general rules . . . ." The publication of GREBE and

Pfeil strongly influenced a number of texts on silviculture, particularly Gayer's notable work on "Diagnosis of Forest Stands" which appeared in 1876.

Research in forest soils by Ebermayer, Müller, and Ramann had accumulated at the end of the past century a great deal of factual knowledge. Ebermayer's "Study of forest litter" (1876) and "Scientific foundations of forestry and agriculture" (1882) have not lost their significance even at the present day. Müller's monograph on forms of humus (1878) revealed the biological nature of forest soil development and opened a new chapter in general soil science. Ramann's comprehensive text "Forstliche Bodenkunde", published in 1893, consolidated the existing knowledge and outlined the general course of the subject. The work of Ramann, Ebermayer, and Müller was continued by a number of German, Swiss, and Scandinavian students, particularly Albert, Aaltonen, Burger, Lang, Leiningen, Krauss, Schwappach, Süchting, Vater, Hesselman, Tamm, and Bornebusch.

About 1880, Grandeau introduced the subject of soils to French foresters and "Les sols forestiers" by Henry appeared in 1907.

At the turn of the century, the subject of forest soils received a great stimulus when the climatic-zonal principles of soil development were discovered by Dokuchaev (1879) in Russia and Hilgard (1892) in America.

The findings of Dokuchaev and his associates (Sibirtzev, Ototzky, Kostytchev) were enthusiastically received by Russian foresters and the beginning of the twentieth century was marked by intensive research in forest soils, led primarily by Morozov, Wissotzky, and Kruedener. Glinka (1908) observed in his widely-known text on soils: "The abundant material collected by foresters on the relation of soils and forest vegetation exceeded by far that accumulated in regard to other types of vegetation. In the reports of Morozov and his followers the problems of soils are intimately welded to those of silviculture." Among the numerous students of soils in Russian forestry schools, Gedroiz (1912) cast an entirely new light upon the relation of soils to plant nutrition by his investigations of colloids and exchange reactions. As Marbut (1936) stated, "In the pioneer chemical work of Gedroiz . . . with a previously unknown method real soil chemistry was created."

A wealth of observations on the relation of tree growth to soils and climate in the Old and New Worlds was collected by Mayr (1890). His "Silviculture on a Scientific Basis," written in 1909, considers the factors of environment in terms of concrete data. The publication of Mayr's text was preceded by another outstanding book, Wagner's: "Areal regulation of forest" (1907). Wagner placed foremost emphasis upon the significance of enviromental forces in selective logging and natural regeneration of forest stands.

The Danish text on environmental requirements of plants, published by Warming in 1895, stimulated numerous studies in the field of plant ecology. The unique work by Schimper (1903) is one of many to be mentioned. The investigations of ecologists provided an important link in the chain of studies on the relation of forests to environment. Two forest ecologists, Sukachev (1913) of Russia and Cajander (1909) of Finland, devised botanical site classifications directly applicable to silvicultural practice.

During the post-war period (1918-1925), the information accumulated by the students of soils and ecology initiated a new school of thought among the practical foresters of Central Europe and led to a revolt against the outmoded theories of Cotta and Hartig (Orlov, 1924). Three facts provided particularly strong support for drastic changes in the technique of forest management: destruction of vast areas of spruce stands on unsuitable sites by nun-moth epidemics; records from Saxony revealing a considerable decrease in the rate of growth of forests managed on the basis of abstract formulas; a greatly increased productivity in Bärenthoren estate and other forests of Central Europe where the old management patterns had been discarded. Wiebecke (1920), Möller (1922), Wiedemann (1923), and many other German writers denounced the principles of stereotyped forest management. They proclaimed the correlation of tree growth with micro-climate and soil as the road toward the solution of the "riddle of production." These ideas soon penetrated far beyond the boundaries of Germany. Most of the Swiss and French foresters adopted as a standard guide "L'aménagement des Forêts" by Biolley (1920), a book advocating the "coordina-

tion of all the forces involved in wood production" as the basis of sound silviculture and picturing the forest as "a tri-phased unit of soil, atmosphere, and wood-producing community." Especial emphasis was placed at this time on the importance of soils in forest management by Czechoslovakian foresters, notably by NĚMEC, KVAPIL, and MAŘAN. The Russian, Scandinavian, and Finnish foresters from the early days of their silvicultural practice were inclined to recognize the importance of the environment and were thus fortunately spared the many disappointments of their continental neighbors.

Americans, like the people of northern Europe, lived in a much closer contact with virgin soils and original vegetation than the people of western Europe. The basic relationship between the environment and plant growth had been noticed in the New World ever since the early days of colonization. The knowledge accumulated by the settlers and woodsmen was inherited by foresters and developed into a foundation for silvicultural theory. A contribution of great importance to the development of American forestry, as well as the subject of forest soils, was made by HILGARD (1906). This geologist and soil scientist concerned with agronomical problems laid, perhaps unintentionally, the foundations of forest ecology. The chapters on the relation of native vegetation to soils in his classical text probably constitute the most valuable single document yet written on this subject. The general outlook of foresters of America was also strongly influenced by a number of ecologists and physiographers, notably MERRIAM (1898), COWLES (1899), BOWMAN (1911), BRAY (1915), CLEMENTS (1916), and WEAVER (1919). The general trend of contemporary American silvicultural practice was indicated by TOUMEY's (1916) "Foundation of Silviculture upon an Ecological Basis." The recent expansion of the forestry program in the United States has given a strong impulse to studies of forest soils. The last decade was characterized by extensive research in tree nutrition, in the maintenance of nursery soil fertility, the adaptation of tree species to environment, and the technique of reforestation under different soil conditions. During this period, AUTEN, CHANDLER, COILE, GAST, HATCH, HEIBERG, KITTREDGE, LUNT, LUTZ, MITCHELL, ROMELL, STOECKELER, and others workers in America made many contributions to the knowledge of forest soils.

Nature of Forest Soils: — The general concept and the definition of soil have been subject to many alterations. In early writings of agronomists the soil was defined as "a mixture of sand, clay, lime, and humus." The geologists regarded soil as a "product of weathering derived from minerals and containing decomposed remains of plants and animals" (FALLOU, 1862). Pioneers in soil science recognized that "the soil is the weathered surface layer of the earth's crust which has been altered by the influence of water, air, organic matter, and living organisms" (DOKUCHAEV, 1879). Because the changes produced by environmental and biotic agents lead to the translocation of soluble salts and colloids and the development of distinct layers, the soil was referred to as "a sequence of mutually interrelated horizons" (ZAKHAROV, 1931). The definitions formulated by biologically-minded students characterize soil as "a peculiar organism", "a lithosphere penetrated by the biosphere", or "a dynamic system" (STEBUTT, 1930). All of these newer concepts are well founded and enlightening, but not entirely acceptable to a silviculturist interested in soil as a medium for forest growth. In many instances, forested soils are a product of weathering, composed of sand and clay particles and arranged in genetic horizons. Very often, however, forests grow on barren rocks, piles of gravelly detritus, deposits of peat, or even permanently flooded areas (Plate 1). These substrata, disregarded in general definitions of soil, do not appear as rare exceptions, but cover vast areas in different parts of the world and often support forest stands of high commercial value.

Obviously, the existence of such forest sites demands a broader concept of forest soils and a somewhat different approach to their studies and utilization.

In brief terms forest soil may be described as a *portion of the earth's surface which serves as a medium for the sustenance of forest vegetation; it consists of mineral and organic matter, permeated by varying amounts of water and air, and inhabited by organisms; it exhibits peculiar characteristics impressed by the physical and chemical action of the tree roots and forest debris.*

The depth of forest soils is determined by the penetration of tree roots and varies from a few inches to many feet. The lower limit of the forest soil is often delineated by the level of ground water, impermeable bed rock, or a layer containing substances toxic to the roots. As a rule, the essential features of forest soils can be learned by examining the soil to a depth of six or seven feet.

The mineral and organic constituents forming the body or skeleton of forest soils vary within very wide limits. In rock outcrops of forested mountains, the root systems of trees may be the chief source of organic matter, since in such situations the litter is often removed by wind and water. On the other hand, in the peat soils of swamp forests, the mineral material appears as a negligible ash fraction of plant remains. In fine-textured soils, the content of organic matter usually varies from 3 to nearly 10 per cent by weight. Both mineral and organic fractions occur in forest soils in practically all states of division; boulders, partly rotted logs, and ultra-microscopic particles of colloidal clays or humate suspensions are the extremes. The liquid phase of forest soils consists of a rather heterogeneous mixture of water and weak solutions of salts, acids, and gases. Most of the air volume is made up of oxygen, nitrogen, argon, and carbon dioxide. The chemical composition and state of fertility of forest soils exhibit every conceivable variation: some soils are composed of nearly pure silica and support struggling stands of the least exacting species; others present a complex involving numerous mineral and organic compounds and have a potential productivity comparable to the rich blackearths of prairie regions.

The soil occupies a position on "the twilight of life" (Marbut, 1936). It is a natural body in which the paths of the non-living mineral world and the living organic world cross. This is especially true of forest soils harboring a multitude of organisms, *viz.,* bacteria, fungi, protozoa, nematodes, worms, insects and rodents. The total weight of organisms per unit of area, referred to as "biological pressure", serves as a fairly accurate expression of the natural soil fertility.

The approximate composition of a forest soil is outlined in Table 1.

The body of soil receives energy from two primary sources: radiation of the sun and decomposition of minerals and rocks. The amount of energy transmitted daily from the sun to the earth exceeds 400 million million horse power. A portion of this vast quantity of energy is trapped by the forest by means of photosynthesis and incorporated into the soil as humus. On the other hand, the bulk of parent soil material is composed of aluminum-silicate minerals, *i.e.* endothermic compounds which were formed by crystallization from magma at high temperature and pressure. The decomposition of these minerals in weathering is, therefore, accompanied by a release

of energy. In the weathering of feldspar, for instance, 120 calories are liberated per gram of material (NIKIFOROFF, 1942). Of course, the energy released in weathering processes is very small in comparison with the energy of radiation.

The composition of forest soil is subject to constant changes, caused by the growth of trees and ground cover vegetation, activity of organisms, and effects of climatic agents. Under the influence of these factors, minerals and organic remains undergo gradual decomposition or disintegration. Some of the released soluble salts and colloids are carried downward by percolating water and are deposited to form definite layers of *genetic horizons*. This translocation of mobile fractions constitutes the most significant process of forest soil development. Undeveloped or young soils are not separated into distinct layers and are called *embryonic soils*. As the differentation into

TABLE 1. — *Approximate Composition of a Slightly Acid Hardwood Loam Derived from Granitic Rocks (Surface Layer)*: —

SOLIDS
50% by Volume

Inorganic
95% by Weight

- *Sand and Silt* 70% by W.
  - Feldspar
  - Micas
  - Quartz and accessory minerals
- *Clay* 30% by W.
  - Silica, Kaolin,
  - Iron and Aluminum oxides,
  - Clay minerals

Organic
5% by Weight

- *Humus*
  - Lignin
  - Cellulose
  - Sugars
  - Resins, Waxes
  - Proteins, Ash
- *Organisms*
  - Roots, Bacteria,
  - Fungi,
  - Actinomycetes,
  - Algae, Protozoa,
  - Nematodes,
  - Earthworms, Insects,
  - Rodents

LIQUID (20% by V.)
Dilute solutions of salts, acids and gases.

Sulfates, Nitrates, Chlorides; Bicarbonates of Calcium, Magnesium, Potassium, and Sodium. Traces of Phosphates and other inorganic and organic compounds. Concentration of salts about 300 p.p.m.

GASES (30% by V.)
Air somewhat enriched in carbon dioxide.

Oxygen	20.0%
Nitrogen	78.6%
Argon	0.9%
Carbon dioxide	0.5%

Traces of Ammonia, Hydrogen, and Hydrogen Sulfide.

humus-infiltrated, depleted, and enriched horizons becomes pronounced, the soil attains a characteristic *profile* which reflects the influences of environmental factors. Such soils are designated as *mature* or *genetically crystallized soils.*

Because of the intimate relationship between soils, climate, and vegetation, soils tend to be distributed on the earth's surface in belts or *zones* correlated with the climatic-vegetational zones. Soils of the taiga region with northern coniferous forests, soils of the tropical rain forests, and soils of the prairie-forest transition are examples of zonal soil groups. Within each of such broad zones, local conditions of topography, drainage, parent material, and forest cover give rise to a definite association of individual genetical soil types characterized by distinctive profiles. The taiga zone, for instance, includes an association of strongly leached ash-like podzols, moderately leached podzolic soils, weakly podzolized soils, rendzina soils of limestone outcrops, various types of gley soils influenced by ground water, and peat soils.

Forest soils cover about one-half of the entire land area of the globe and are bounded by non-forest soils, namely those of tundra, marshes, meadows, prairie, and desert. Approximately one-fifth of the total forest soil area is occupied by farms, although as much as one-third has potential agricultural possibilities. The remainder comprises "absolute forest land", *i.e.*, soils of the mountains, rough glacial deposits and swamps, unsuitable for agricultural use.

Importance of Forest Soils in Silviculture and Related Branches of Land Utilization: — The theoretical foundations of forest soils comprise the following three more or less independent aspects: (1) *the genesis of soils, i.e.,* their origin, development, and profile characteristics produced under the influence of climate, topography, ground water, parent rock, and vegetation; (2) *the properties of soils, viz.,* their physical, chemical, and biological characteristics; (3) *the effect of soils upon the forest vegetation,* namely, upon the composition of the forest stands and ground cover, rate of tree growth, quality of wood, vigor of natural reproduction, resistance of stands to diseases, and other silviculturally important features. The applied knowledge of forest soils involves two broad phases: (1) *management of forest nursery soils,* including regulation of watering, application of fertilizers, soil inoculation, cultivation, and control of parasitic organisms; (2) *soils in relation to silvicultural practice, i.e.,* planting of trees, management of forest stands, and silvicultural cuttings.

The practical value of the knowledge pertinent to forest soils has never been clearly outlined and deserves a detailed discussion.

The reasons for study and planned management of forest soils are numerous. According to Morozov (1912), the forest is "man's most wonderful gift from nature." Millions of people throughout the world receive from the forest their daily bread, shelter, fuel, clothing, and numerous other commodities. With the progress in wood technology, forest products have penetrated every phase of life and the possibilities of further developments are far from being exhausted. Regardless of population density and the availability of means and materials that may replace wood, the forest will continue to occupy its place of economic importance because of several conditions: it has a much greater capacity to utilize soil nutrients than do field crops; it is a faster producer of cellulose than any other association of plants; it requires minimum expenditure of human energy per unit area and allows mass production on extensive tracts.

The forest provides a number of benefits which cannot be reckoned in terms of dollars and cents. Forest controls erosion, and conserves moisture which becomes the life blood of cultivated crops. Being an outlet for labor, the forest serves as a buffering agent moderating disturbances of economic equilibrium in time of depression. The role of the forest as a social factor was remarkably outlined centuries ago by Gautama. In the words of the founder of Buddhism, "The forest is a peculiar organism of unlimited kindness and benevolence that makes no demands for its sustenance and extends generously the products of its life activity; it provides protection to all beings, offering shade even to the axeman who destroys it."

The maximum direct and indirect benefits from a forestry enterprise can be attained only by management on a sustained yield basis or by "use without abuse". The technique which satisfies this requirement is skillful logging which perpetuates the uninterrupted existence of a forest tract as a whole and assures its maintenance through natural regeneration. The conditions of soil play their most important part in this phase of silvicultural practice, even though the present concrete knowledge of soils in relation to logging is in its embryonic stage. The cuttings which are based only on

the above-ground features of forest stands may ruin the natural fertility of soil, initiate soil erosion, or alter adversely the level of ground water. Such cuttings seldom assure the success of natural reproduction. As stated by KOROLEFF (1935), "the forester cannot intelligently select even a more or less suitable cutting stencil from his book collection unless he has an adequate theoretical and practical knowledge of various forest soils and of the whole complex relationship between these and the life of the various trees and other plants of the forest.... The knowledge of the underground life of a forest is the only key to adequate understanding of its above-surface life."

One of the reasons that empirical cutting practices are nearly universal is to be found in the sluggishness of the forestry educational system. Forest schools until recently were underrating the importance of the major factor in wood production, the soil, and the teaching of silviculture was, literally speaking, superficial. The silviculturists that "did not see the forest for the trees" became proverbial. HERBERT (1936) gave a frank and vivid account of the situation that existed in the not distant past: "Foresters are slowly coming to realize that a knowledge of soils is absolutely essential to all silviculture and management. How well I remember the many hours of careful measurements we used to make to determine the growth and volume of a stand and then kick our heel into the ground, grab a fist full of soil and litter and determine the soil that made this growth possible in the twinkle of an eye!" Similar ideas were expressed by HAWLEY and COOVER (1934), TKACHENKO (1935), OUDIN (1938), and many others.

The importance of soil characteristics is more obvious in reforestation than it is in logging since indiscriminate planting is usually paralleled by the failure or stagnant growth of plantations. The ultimate aim of reforestation practice is not to obtain the mere survival of trees, but the production of the highest possible yields of sound and valuable timber. This can be accomplished only by a careful matching of soil conditions and tree species. Because reforestation is practiced on thousands of acres and is a long-term investment, any negligence in the selection of planting sites may result in huge financial losses. Should the investigation of soil conditions, however, bring but five per cent increase in the survival and growth of trees (which is a very conservative estimate), the economy would attain substantial figures.

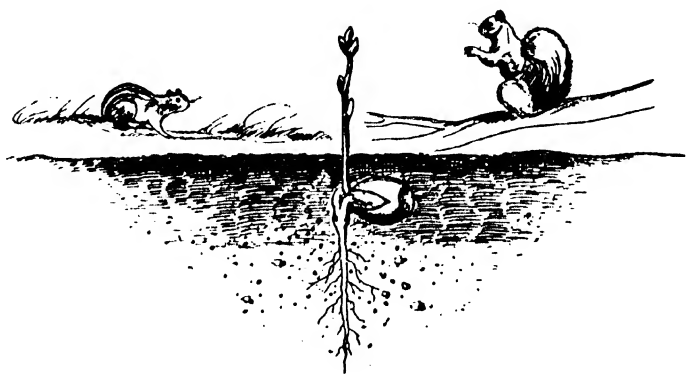
Among the problems of forestry, few are as difficult as the management of nursery soils, particularly those in permanent nurseries. In order to succeed in growing seedlings year after year on the same area, it is necessary to apply regularly considerable amounts of commercial fertilizers as well as toxic substances for the control of parasites. All of these chemicals enter into numerous reactions with the soil constituents and cause a partial or complete destruction of the parasitic as well as the useful organisms. Under these circumstances the productive capacity of a soil may be maintained only if the intricate chemical and biological reactions and interrelationships are thoroughly understood and properly adjusted.

The expense involved in purchasing and applying disinfectants and fertilizers in some nurseries amounts to several hundred dollars per acre. This expense, however, is well justified considering the high value of the

product. One acre of a forest nursery produces more than 1,000,000 two-year-old seedlings. The minimum cost of two-year-old seedlings, according to present price lists of private companies, is $4.00 per thousand. Thus, the gross income from one acre of nursery soil in two years amounts to at least $4,000; the gross income of a nursery, forty acres in size, may reach $100,000 per year. One acre of a forest nursery produces enough seedlings to reforest one thousand acres, and consequently, the care given to a forest nursery of average size may decide the future of forest stands worth millions of dollars.

Recent years have seen a remarkable increase in the planting of forest vegetation for purposes other than lumber or pulp production. This country, in particular, has vigorously promoted programs of extensive park systems, "broad-acre" cities, resettlement movements, shelterbelt and roadside plantings, farm woodlot management, erosion control, and wildlife conservation. All of these projects demand a rapid growth of planted stock and their success is dependent upon the knowledge of soils. The same may be said in regard to a number of endeavors that lie on the border line between silviculture and farming, *viz.*, production of fruits, nuts, berries, syrup, rubber, tung oil, tannin, and other valuable chemical compounds provided by forest plants.

Although the techniques of silviculture and farming are not comparable, many basic problems of field crop growth, soil analysis, and application of fertilizers may, according to HILGARD (1906), be approached more successfully by the study of "objectum naturae" — virgin forest soils rather than "objectum artis" — soils distorted by cultivation. The conditions which make forest cover a unique indicator of soil productivity are the presence of many tree species, characteristic ground vegetation, and the permanent record of the stand's growth written by the heights and annual rings of the stems. To these attributes of forest cover, soil science is indebted for a great deal of information pertinent to the nutrition and water requirements of plants.



Chapter II

GENESIS OF FOREST SOILS

> "The eternal genetical relationships that exist between the forces of environment and physical matter, living and non-living domains, plants and animals and man, his habits and even his psychology—these relationships comprise the very nucleus of natural science."
> V. V. DOKUCHAEV

Weathering and Soil Development: — The earth's crust or the lithosphere is composed of about ninety elements combined as minerals and existing largely in the form of rocks. Under the influence of environmental forces, the surface strata of the lithosphere undergo *weathering*, a process which tends to release the original mineral constituents and to rearrange them into new compounds (JENNY, 1941). In the picturesque language of FALLOU (1862), "the tooth of time incessantly grinds the crust of our planet and gradually destroys its solid mass." Changes in temperature, expansion of water on freezing, erosive action of wind and rain — all contribute to the rupture and disintegration of rocks into finer material, *i.e.*, gravel and sand. This physical weathering is usually accompanied by more profound changes caused by chemical processes, such as solution, hydrolysis, carbonation, hydration, oxidation, and reduction. In chemical weathering, water, oxygen, carbon dioxide, and various acids, supplied by the environment, react with the silicates and other minerals of the parent rocks. Chemical processes are largely responsible for the formation of the very fine or colloidal particles. The final products of weathering consist of both undissolved minerals and mineral substances in solution, as follows:

(1) *Minerals:* quartz, orthoclase, plagioclase, muscovite, biotite, augite, amphibole, apatite, pyrite, magnetite, hematite, limonite, chlorite, serpentine, and hydrated alumino-silicates or clay minerals, such as kaolinite, montmorillonite, and hydrous mica; the latter two have high base exchange capacity. Some of the minerals, especially the hydrated alumino-silicates, are formed from the original minerals in the course of weathering.

(2) *Soluble products:* silicic acid, and salts of alkali, alkaline earth, and other metals, especially K_2CO_3, Na_2CO_3, $Ca(HCO_3)_2$, $CaSO_4$, $Mg(HCO_3)_2$, $Fe(HCO_3)_2$, $FeSO_4$, and $Ca_3(PO_4)_2$.

Weathering is a geological process extending to a considerable depth into the earth's strata. It plays a far-reaching but rather indirect part in the development of the soil proper, *i.e.*, in the translocation of salts and colloids within a shallow surface portion of the weathered mantle. The chief importance of weathering rests in its effect upon the formation or destruction of the clay minerals which determine to a great extent the base exchange properties of the parent material and the potential productivity of the soil (GEDROIZ, 1929; WIEGENER, 1929; STEBUTT, 1930).

The composition of the final products of weathering depends to a great extent upon the conditions of climate. Climatic factors produce within the boundaries of forest regions three fundamental types of weathering as regards the colloidal properties of the soil material: (1) *Physical disin-*

tegration; (2) *Kaolinization, or more correctly, formation of clay minerals;* (3) *Laterization.*

(1) *Physical disintegration* is the predominant process in cold boreal regions or high mountains; it proceeds under conditions that inhibit chemical reactions and results in the accumulation of coarse, mineralogically unaltered material. This type of weathering ultimately produces sandy—gravelly or "skeletal" detritus with a low content of clay particles, and hence a deficiency of base exchange constituents (LANG, 1920).

(2) *Kaolinization* is prevalent in temperate regions; it is characterized by the partial desilication of parent minerals (ZAKHAROV, 1931) and the synthesis of new alumino-silicate minerals which possess base exchange properties. Montmorillonite, hydrous mica, and kaolinite are the representative clay minerals thus formed. This type of weathering produces "siallitic" (Si-Al) parent materials of sandy loam or loam texture high in base exchange capacity.

(3) *Laterization* is confined to hot, humid tropical and subtropical regions; it involves intensive hydrolysis and the destruction of the alumino-silicate nucleus with subsequent desilication and release of hydrated aluminum and iron oxides (HARRASSOWITZ, 1926). This type of weathering produces "ferrallitic" (Fe-Al) materials of loam or clay texture having low base exchange capacity.

Differentiation of Soil Profile: — A distinct line should be drawn between the *weathering process* and *soil-forming processes.* Regardless of the type of weathering, the mantle rock or parent soil material may undergo one or more of the three basic processes of profile development common to forest soils: (1) incorporation of humus or *melanization;* (2) leaching or *podzolization;* (3) deoxidation by ground water or *gleization.*

Young or embryonic forest soils of denuded slopes or recent deposits have only two layers; the upper, an accumulation of plant remains, called litter; the lower, mineral substratum. After the soil has supported vegetation for a longer period of time, the litter becomes partly decomposed and the humified material is gradually infiltrated by percolating water or incorporated by organisms into the upper portion of the mineral soil, thereby forming a dark, partly mineral and partly organic layer. This darkening or *melanization* of the soil surface constitutes the initial phase in the development of the soil profile, common to forest soils of all regions. In some instances, the conditions of climate, vegetation, or parent rock arrest the development of the soil profile in this initial stage, and thus give rise to humus-incorporated or *melanized soils* of skeletal, kaolinized, or lateritic substrata.

Under other conditions, perlocating water, reinforced with carbon dioxide and organic acids, gradually leaches a portion of humus and mineral salts from the upper soil layers. At a certain depth the mobile fractions are precipitated or flocculated due to the presence of bases or other factors. As a result of this translocation of mineral and organic substances, called *podzolization,* the soils show two additional layers: a leached or eluvial horizon and an accumulative or illuvial horizon. The process of podzolization may affect parent material produced by any type of weathering with the resulting development of *podzols, podzolic soils, skeletal or mountain podzols,* and *podzolized laterites.*

Aside from the action of the percolating water, the character of the soil profile may be influenced by ground water. Capillary action may carry dissolved salts to the upper part of the soil profile, where they are recrystal-

lized by evaporation. Some of these salts may be permanently fixed into insoluble compounds. The ground water also translocates colloidal particles in its periodic fluctuations and causes the hydrolysis and reduction of some chemical compounds, forming sticky and mottled "gley" horizons. These changes of soil profile, or *gleization*, constitute the third important process which may affect the development of forest soils and produce hydromorphic soils such as *gley podzols, gley-melanized soils,* and *gley-lateritic soils.*

Soil Horizons; Their Characteristics, Designation, and Importance in Silviculture: — The horizons of forest soil are designated according to GLINKA (1931) by different letters:

A_0 Undecomposed and partly decomposed organic debris, such as forest litter, duff, and peat. This layer is subdivided sometimes into A_{00}, *i.e.*, undecomposed organic remains or "litter," and A_0, *i.e.* partly decomposed organic remains or "duff".

A_1 Humic or "melanized" horizon consisting of mineral matter intimately mixed with humus. This "top soil" horizon is of a dark color and is usually high in nutrients.

A_2 Leached, "podzolic" or eluvial horizon, depleted in soluble salts and organic matter. It is commonly coarser in texture than the underlying layer. If leaching is intensive enough to remove iron compounds, the horizon attains a light color; in extreme cases it becomes ashy-grey or white.

B Enriched, "accumulative" or illuvial horizon, containing precipitated soluble salts and coagulated colloidal humus. Depending on the nature of soil-forming process, it may be structured, compacted, or cemented, and thus may form impervious strata, referred to as "hardpan", "ortstein" or "claypan". The color of the accumulative layer tends to be brownish or reddish. This horizon is sometimes subdivided into B_1, B_2, etc., depending upon its chemical and morphological composition; such detailed subdivision, however, is of little practical significance unless it is warranted by ecologically important differences in the composition of sub-horizons.

C Parent material of soil, consisting of either unweathered or weathered mineral matter. This layer may be subdivided into C_1 or C_2 to distinguish the strata of different geological origin, or to distinguish the weathering part from the solid bed rock.

G Water-logged or "gley" horizon, formed by the influence of ground water and characterized by the presence of ferrous iron and other reduced compounds. It occasionally has some organic matter and may contain H_2S, NO_2 and other products of anaerobic decomposition. It is characterized by greenish, bluish and reddish mottling; in some instances, however, the mottling is masked by infiltrated organic matter. The seasonal fluctuations of ground water may produce distinct eluvial or impoverished gley layers, and illuvial or enriched gley layers, designated as G_1 and G_2. The accumulation of salts in the surface layers of alkali soils, as well as the formation of ferrallitic crusts of iron and aluminum oxides in laterites, may also be regarded as forms of gleization.

The original version of this system of profile designation was introduced by DOKUCHAEV (1879) in connection with the study of chernozem soils, *i.e.*, soils comprised of three (A, B and C) horizons. When the same method was extended to forest soils with four or more layers, the letters were sub-classified by numerical symbols and the system became somewhat cumbersome. Further complications arose when DOKUCHAEV's scheme was applied to soils of arid climates (NIKIFOROFF, 1931). As a result numerous modifications and substitutes were proposed at different times. In the KOSSOVICH (1911) adaptation, the leached horizon was designated by the letter B instead of A_2; the accumulative horizon and parent material were subsequently designated by the letters C and D. A careful reading of a profile description is, therefore,

always necessary to determine which system of designation is followed. HESSELMAN (1926) suggested the use of the term F-layer for the undecomposed and partially decomposed forest debris, and H-layer for humified remains. However, in many instances, the boundary between these two sub-horizons is poorly defined, and their separation is more justified in special humus studies than in general soil investigations. In some recent writings the surface litter, or L-layer is separated from the partly humified, fermenting F-layer. WISSOTZKY (1927) devised a new Latinized nomenclature for all horizons of the forest soil profile, but retained the original A, B, C letters for the well-drained mineral portion of the soil. The entire abandonment of the original scheme was advocated by SOKOLOVSKY (1931) who proposed the designation on a phonetic basis, such as H — humus layer, E — eluvial layer, P — parent material, and so forth. Similar plans were suggested by other pedologists.

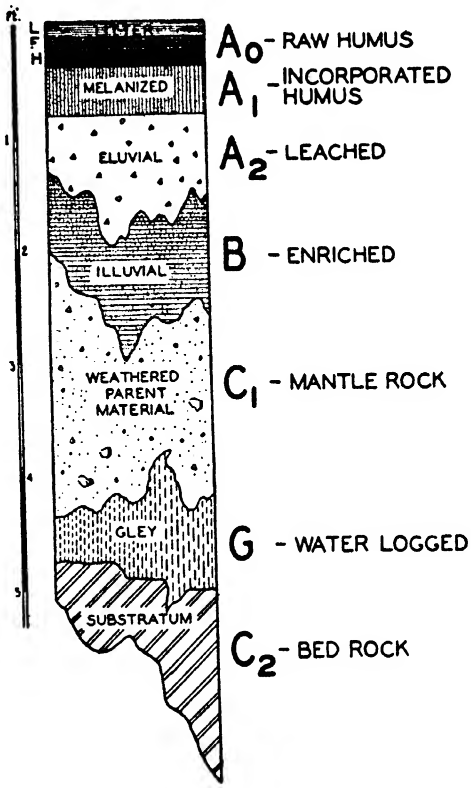


FIGURE 1. — Designation of horizons in the profile of a leached forest soil influenced by ground water.

In spite of some obvious advantages, most of the recent proposals are likely to find only a limited application. Long-time tradition and thousands of already published papers, using the original designation, are the chief obstacles to the introduction of a new method. Furthermore, the DOKUCHAEV designation, no matter how awkward at times, reflects the inherent sequence of soil development, and has a more logical foundation than purely empirical schemes. Fortunately the standard designation presents no unavoidable difficulties in application to forest soils. Figure 1 shows the designation of horizons in a profile of a leached forest soil influenced by ground water.

Sometimes the soil horizon is penetrated by inter-layers or intrusions of other

horizons, *viz.*, spots of podzolized material in the infiltrated layer, strips or "pseudo-fiber" of ortstein in the leached layer, or regions of gley in the accumulative layer. Such compound horizons are designated usually by the two letters, *viz.*, A_1A_2, A_2B, and BG. The boundaries of soil horizons seldom follow a horizontal or a straight line; rather they form an undulating or even a zigzagging contour (LUTZ, 1940). Therefore, in the descriptions of soil profiles or in schematic drawings it is desirable to indicate the minimum and maximum depth of both the upper and the lower boundaries of soil horizons, as well as their general outline.

The recognition of soil horizons is important not only in the abstract genetical studies of soil "as an independent natural body", but in practical silviculture as well. The composition of forest stands, their rate of growth, possibilities of natural reproduction and silvicultural management are intimately dependent upon the amount of forest litter and other raw organic remains, depth of incorporated humus, composition of the leached and accumulative layers, nature of parent material, and the proximity of the gley horizon. No correlation between the physical, chemical, or biological properties of soil and forest growth can be established, or comparable data obtained, if the composition of separate soil layers is disregarded in soil analyses (SALISBURY, 1922; BORNEBUSCH, 1931; WILDE, 1931; KRUEDNER, 1934a; WISSOTZKY, 1934; LUTZ *et al.*, 1937; MAŘAN, 1938).

Soil as a Function of Environmental Factors and Time: — The first basic law of soil science, formulated by DOKUCHAEV (1879) states: "The soil is a result of reactions and reciprocal influences of parent rock, climate, topography, plants, animals, and age of the land." Mathematically speaking, the soil (S) is a function of geological substratum (g), environmental influences (e), biological activity (b), and time (t):

$$S = \int (g.e.b.)dt$$

Although the discussion of soil development must be subdivided into climatic, topographic, geological, and vegetational aspects, no such division exists in nature. Therefore, the classification of soil on the basis of climate or any other single factor, no matter how influential, has only a general or a schematic significance. This is especially true in dealing with forest soils. The forest itself is a factor of tremendous modifying power which may bring podzolization into a region of prairie or lateritic soils; vice versa, it may arrest the leaching and promote the blackearth-like process of humus incorporation in the heart of the podzol or laterite region (TKACHENKO, 1908; MEJSTŘÍK *et al.*, 1929; GIESECKE, 1930; GAST, 1937; AUTEN, 1940).

Relation of Soils to Climate: — Among climatic factors, the conditions of temperature and moisture exert a particularly profound influence upon the distribution of plants and the development of soils (SCHIMPER, 1903; LIVINGSTON and SHREVE, 1921; RUBNER, 1925; TANSLEY and CHIPP, 1926; VILENSKY, 1925; JENNY, 1929; I. B. S. S., 1934).

A certain minimum amount of total heat is one of the prerequisites determining the existence of forest and hence the occurrence of forest soils. In arctic regions and on high mountains, the forest is replaced by heath shrubs, mosses, and lichens, as soon as the average temperature of the growing season drops below 50° F. (MAYR, 1909). The

soils of such ***microthermal*** conditions include ***skeletal barrens, wet tundra*** or ***muskeg soils,*** and ***dry tundra soils.*** Of equal importance to the forest distribution is the humidity of the climate, *i.e.*, an excess of preciptation over evaporation (Hilgard, 1892; Meyer, 1926). In ***arid*** or ***semi-arid*** climates, deficient in available moisture, the vegetative cover consists of grasses, xerophytic shrubs, cacti, or halophytic plants inhabiting ***chernozems,*** other ***grassland soils, desert soils,*** and ***alkali soils.*** The general tendency of these non-forest soils is to accumulate salts in their surface layers through either the action of plants or the evaporation and recrystallization from solution.

On the other hand, the humid climates, with their excess of precipitation over evaporation, are conducive to the development of forest vegetation and the formation of forest soils. Within the humid regions, both the amount of rainfall and the temperature exert a decisive influence upon the composition of forest cover and the nature of soil development (Ramann, 1918).

The *cold* portion of the humid region is correlated with the occurrence of the boreal, largely coniferous forest, and with the predominance of *podzol* soils. Podzols are characterized by an ashy-gray siliceous surface layer depleted in iron and aluminum sesquioxides, as well as other soluble substances, and a cemented or compacted B

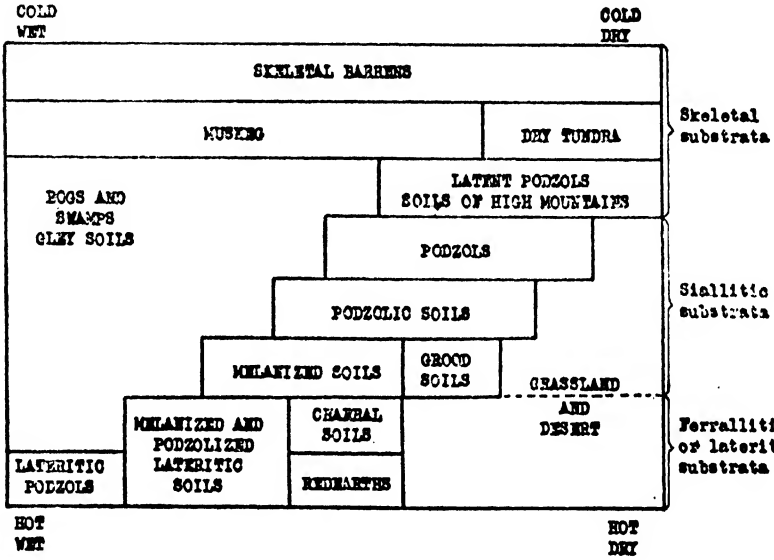


Figure 2. — Schematic outline of the distribution of the major groups of forest soils in relation to temperature and moisture.

horizon. Near the northern limits of forest, podzols lose their pronounced characteristics and are called *latent podzols.* Along the southern boundary of the podzol zone the conifers are mixed with broadleaved species; accordingly, the fully-developed podzols are largely replaced by less strongly leached *podzolic soils.*

The *warm* portion of the humid region is occupied by the tropical and subtropical forests growing on ***lateritic soils,*** *i.e.* soils of red colored substrata impoverished in silica and bases but enriched in iron and aluminum sesquioxides. Depending upon the periodicity of rainfall, lateritic soils support either rain forest, monsoon forest, or savannah forest. Rain forest is confined to continuously humid areas, and is supported by ***humus-enriched*** and ***podzolized lateritic soils.*** Savannah forest occurs in areas with prolonged periods of drought; the ***redearth soils*** of this formation are very low in humus and tend to form concretions and crusts of iron and aluminum oxides near the surface. Monsoon forest and soils developed under it occupy an intermediate position. In the

periodically dry areas on the border between the tropical and temperate zones, the redearths are replaced by moderately laterized red or brown *charral soils* supporting sclerophyllous forest.

The zones of podzolic and lateritic soils are separated by a more or less continuous transitional belt of *melanized soils* supporting mesophytic forests of deciduous trees with some pines, firs, and a few other conifers. Melanized soils show only a slight leaching of easily soluble bases and are distinguished by a dark surface layer with incorporated humus. The continental sub-humid region of steppes and prairies is bordered by nut-structured prairie-forest or *grood soils;* these soils form a transition between chernozems and podzolic soils and support largely oaks and associated hardwood species.

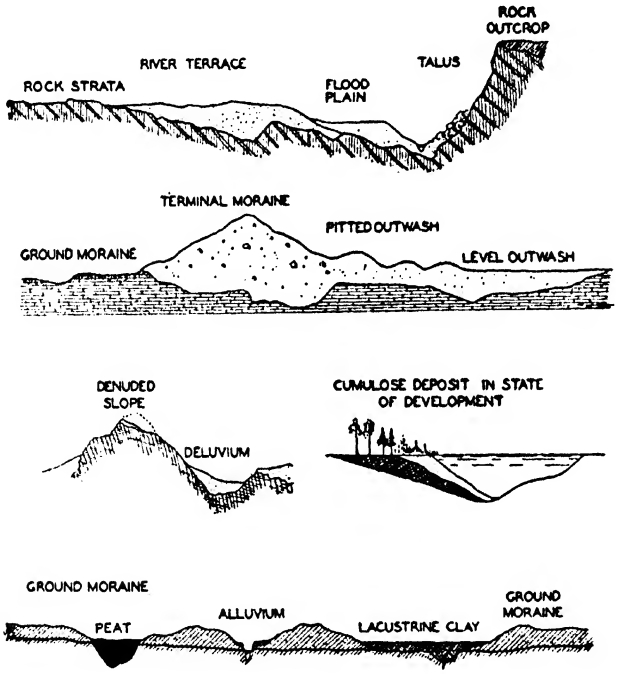


FIGURE 3. — Topographical features of the surface geological formations.

The increase in elevation and the accompanying changes in the state of climatic factors are followed by synchronized changes in the composition of forest vegetation and the nature of soils. Mountain or "subalpine" forests in the proximity of timber lime consist of a limited number of cold resistant species. The stands of this region struggle against the severe environment of high altitudes on slightly weathered, shallow detritus of rocks or *skeletal soils.* Figure 2 outlines in a schematic form the distribution of the major groups of forest soils in relation to temperature and moisture.

Under the influence of topography, parent material, and other local soil-forming factors, the climatic-zonal groups break down into a number of morphological varieties and are interspersed with embryonic or immature soils, gley soils, and organic soils.

Soil-Forming Role of Topography: — The surface of the earth (Plate 2) presents a mosaic of rock outcrops, weathered debris, and deposits of fluvial, glacial, aeolian, deluvial, and cumulose origin (BOWMAN, 1911;

Emerson, 1920; Longwell *et al.*, 1937). These formations impart to the parent material certain topographic features (Figure 3) determining the so-called "micro-zonal" course of soil development (Kruedener, 1926).

The topography serves as a multi-faceted prism dispersing or concentrating the effects of climatic factors. It directs the course of run-off water and determines the content of soil moisture, the depth to the ground water table, and the amount of soluble salts, colloids, and organic matter deposited by erosion processes. All of these conditions exert a profound influence upon the distribution of vegetation and the morphology of the soil profile. Two examples illustrate micro-zonality in the distribution of soils (Figure 4).

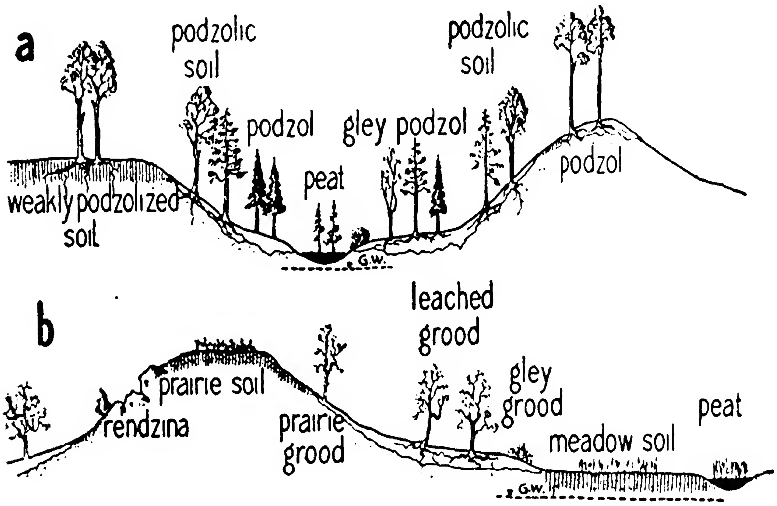


Figure 4. — Influence of topography upon soil development: a. glacial deposits in podzol region; b. unglaciated limestone in prairie-forest transition.

A morainic landscape in the podzol region is characterized by the presence of peat soils in depressions. Gley soils are confined to the borders of swamps. Strongly leached podzols occupy the lower slopes, where the rate of water percolation and leaching are intensive, or the light-textured, gravelly morainic ridges, predisposed to the invasion of podzol-forming conifers. Slightly podzolized soils commonly occur on the flatter uplands (Figure 4, *a*).

The rough calcareous deposits in a transitional prairie-forest zone may show an even greater variety of soil conditions within a comparatively small area. The elevated plateaus are, as a rule, occupied by prairie soils overlying a limestone substratum. The nut-structured grood soils are confined chiefly to the lower slopes. On the northern slopes with their deep snow cover, groods may be replaced by podzolic soils. The dry, and often barren southern exposures are correlated with limestone outcrops or shallow immature rendzina soils. Lowland prairie or wet meadow soils are found in the valleys and lower plains on which eroded calcareous material accumulates (Figure 4, *b*).

Influence of Parent Material: — Soils inherit from parent material certain important properties (Tamm, 1921; Cobb, 1931) determining their depth, texture, and sometime mineralogical composition. Nevertheless, the effect of the parent rock upon the ultimate genetical morphology of the soil profile is subject to wide variation.

The soil profiles which develop under unbalanced or extreme climatic conditions are influenced by the parent material only to a limited extent. The upper mineral layers of mature podzols are composed of nearly pure silica regardless of the nature of parent material. Similarly, on all substrata the upper layers of the chernozems and alkali soils accumulate humus and soluble salts, respectively. On the other hand, the soils occurring in regions with a mild climate, *viz.*, melanized or weakly podzolized soils, preserve many important properties acquired from their parent rocks, as was pointed out long ago by FALLOU (1862).

Calcareous rocks and deposits exert a most pronounced and lasting influence upon the soil. Their high content of carbonates tends to maintain the original alkaline reaction and inhibit the leaching of salts and colloids. As a result, parent materials of calcareous origin develop in some climatic zones into so-called "endodynamogenic" varieties of soil (GLINKA, 1931). Such soils differ in their profile features from the regional soils formed on non-calcareous rocks. Soils with "alpine humus", limestone outcrops with alkaline raw humus, and black humus-calcareous *rendzinas* are the morphological varieties formed on alkaline substrata in the region of podzols. Because an alkaline reaction is apt to favor the growth of grasses rather than trees, calcareous deposits and rocks often give rise to *prairie soils* within the region of podzolic soils (MARBUT, 1935). The occurrence of such intra-zonal prairie soils is especially common near the boundary of true prairie soils or chernozems. *Terra rossa* is a variety of soil derived from calcareous substrata in the region of lateritic weathering (LEININGEN, 1917; BLANCK, 1930). Basic or ferro-magnesian rocks behave more or less similarly to calcareous materials. In mild climates and under hardwood forests, basalt, andesite, and similar rocks often develop into soils resembling rendzinas or humus-calcareous soils. In general, however, the resistance to leaching of ferro-magnesian parent material is considerably lower than that of limestone. The siliceous rocks, especially sandstones, are affected by environmental conditions in a comparatively slight degree because of the inert nature of silica. The granitic rocks produce, in different climatic regions, soils having a wide range of profile variations.

The influence of parent material in different climates can be clearly seen by comparing mature soils which have developed on limestone, sandstone, and granitic rocks in the podzol, chernozem, and transitional prairie-forest regions (Figure 5). In the semi-arid region occupied by prairie grasses, black earth or chernozem soils develop on all of the three types of rock. The black earths derived from limestone rocks (L) have more bases and a higher content of humus than the soils derived from granitic (G) and especially from sandstone (S) rocks. In the podzol region, with its pronounced leaching, podzols or podzolic soils develop on all of the three types of rock. The soils derived from granitic rocks show the leaching and other features of podzolization most pronouncedly. The soils from sandstone are low in mineral colloids and often manifest the effects of podzolization to a somewhat lesser extent. The soils derived from limestone resist leaching and usually retain bases in the lower part of the soil profile. Along the prairie-forest boundary, calcareous rocks or loessial deposits frequently produce chernozem-like prairie soils, whereas granitic rocks give rise to podzolic forest soils. The sandstone soils, owing to their coarse texture and deficiency of nutrients, support either stands of pioneer trees or an inferior cover of prairie grasses. In either case, these soils develop a thin humic layer, but no other profile characteristics and are classified as "bor sands" when they support forest and "prairie sands" when they support grass vegetation.

Forest Vegetation and Soil Development: — Forest stands of different composition modify the temperature and the moisture content of the soil (Mathieu, 1878; Ebermayer, 1900; Wissotzky, 1938); the effect on soil moisture is particularly important as the trees influence not only the amount of precipitation that reaches the ground and percolates through the soil, but also the position of the ground water table (Ototzky, 1905; Henry, 1903; Pearson, 1907). Different types of forest cover are known to affect soil porosity, its aeration, and permeability (Wollny, 1899; Kvapil and Němec, 1925). The roots of trees and ground cover plants produce various amounts of carbon dioxide which, in water solution, increases the

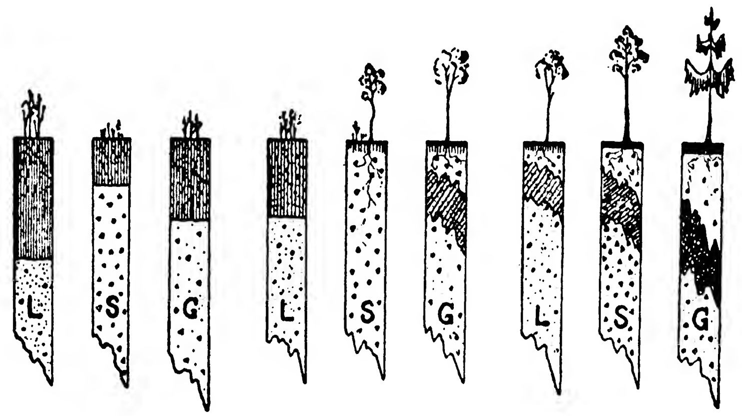


Figure 5. — Influence of parent material of limestone (L), sandstone (S), and granitic (G) origin upon the development of soil profiles in different climatic regions (schematic presentation).

solubility of carbonates, phosphates, and silicates (Kravkov, 1912; Polynov, 1916; Lundegardh, 1931; Lunt, 1937). During the growing season leaves accumulate nitrogen, calcium, magnesium, potassium, phosphorus, sulfur, iron, and other elements. The content of accumulated salts varies greatly with the species, but, on the whole, tolerant trees, such as ash, maple, beech, basswood, spruce, and fir, accumulate considerably higher amounts of nutrients than do light demanding species, such as aspen, paper birch, jack pine, or Scotch pine (Ebermayer, 1876; Ramann, 1911; Deines, 1938). Simultaneously, leaves synthesize widely different organic compounds; the structure of these compounds determines the base exchange capacity of litter, its content of free basic or acidic constituents, degree of acidity, carbon-nitrogen ratio, and the relative resistance to decay (Waksman, 1938). When the leaves fall, their chemical composition plays a significant part in the development of the humus horizon and of the entire soil profile.

The litter of most hardwood species is a suitable medium for soil organisms and, under favorable environmental conditions, it undergoes a rapid

decomposition or "humification". The amorphous humified residue of ligno-protein nature is then incorporated with the soil to form so-called ***mull humus*** (Müller, 1878). This type of humus is characterized by a high degree of biological activity, and a rapid rate of oxidation (Stoklasa, 1930); it has a tendency to retard the leaching of soil or the formation of eluvial and illuvial horizons. Vice versa, the litter of most conifers tends to inhibit the processes of decomposition (Koch, 1914); consequently the raw organic remains accumulate on the surface as ***mor humus.*** This type of humus, with its low biological activity, generates strong reducing agents and encourages podzolization of the soil.

Depending upon the properties of litter, tree species are classified as "soil improving" and "soil deteriorating" or "podzol forming". Such a classification is somewhat ambiguous and should be accepted with certain reservations. The process of podzolization is not necessarily synonymous with the deterioration of forest soil fertility; in numerous instances the contrary is true. In some earlier writings the "soil deteriorating" or "soil conserving" effects of litter were ascribed to differences in its content of bases. As has been outlined, the influence of forest litter embraces complicated physico-chemical and biological reactions in which the bases play only a subordinate role; litter of pronounced "podzol-formers", such as spruce and hemlock, often has the same content of bases and other nutrients as the litter of distinct "soil-conserving" species, *viz.*, beech, hard maple, or basswood. The work of Leiningen (1931) contains a review of many reports dealing with this relationship.

The soil-forming influences of forest vegetation may be offset by the more powerful effects of climate, topography, or parent rock. Occasionally mull humus and slightly leached soils are found under coniferous stands, whereas raw humus and strongly leached soils are found under hardwoods.

Time as a Factor in Soil Development: — In the course of time the soil undergoes manifold changes. In a genetical sense, the soil originates as a formless "embryonic" deposit; it attains "maturity" when its profile shows distinct horizons, and under the influence of denudation processes it may pass into a state of deterioration. Aside from the comparatively slow evolution of the soil profile, the physico-chemical composition of the soil body exhibits marked annual and seasonal changes.

Foresters who are engaged in reforestation and have the satisfaction of observing the successful growth of plantations are well aware of the time element in soil development. Under the protection of an established forest canopy, the depleted soil of burned-over barrens often regains its normal appearance and much of its fertility within the brief period of 15 to 20 years. The effect of "soil dynamics" is still more obvious to a silviculturist in charge of a permanent nursery. In many instances the chemical composition of the soil in such a nursery can be maintained only by means of two or three applications of fertilizers each year.

Chapter III

GENETIC SOIL GROUPS OF THE WORLD; UPLAND SOILS

Genetical Classification of Soils in Relation to Silviculture: — Since the early days of scientific forestry, numerous attempts have been made to delineate natural, physiographically homogeneous regions in which the same silvicultural policies and methods could be applied. However, none of these approached in simplicity and ecological significance the classification of soils on a genetical basis. The genetic soil groups of the world are natural land types determined by climate and vegetation; they are characterized by generally similar soil profiles and, in the words of DOKUCHAEV, serve as a mirror of the environment. If properly delineated, genetical soil types provide a reliable framework for the acclimatization or translocation of tree species, and for the proper selection of logging and reforestation methods. The lack of such a natural basis has been responsible in the past for a number of grave silvicultural mistakes. It is sufficient to recall that silvicultural methods developed on the brownearths of Germany generally failed when applied on podzolic and prairie-forest soils of Russia and, later, on those of the United States. In turn, the foresters of Central Europe experienced many bitter disappointments in their attempts to naturalize American species on soils of radically different genetical nature.

As would be expected, the classification of soils on a genetical basis has followed a long and rather winding road of theoretical and terminological evolution (DOKUCHAEV, 1879; HILGARD, 1892; SIBIRTZEV, 1900; GLINKA, 1908 and 1931; KOSSOVICH, 1911; RAMANN, 1918; AARNIO and STREMME, 1924; VILENSKY, 1925; NEUSTRUEV, 1927; MARBUT, 1928; AFANASIEV, 1927; GEDROIZ, 1929; STEBUTT, 1930; REMEZOV, 1932; BALDWIN, KELLOGG, and THORP, 1938, and others). Some of the modifications introduced into the original DOKUCHAEV-SIBIRTZEV-HILGARD pattern have increased the scope of useful knowledge; others have brought unnecessary confusion (GLINKA, 1931, p. 293 *et seq.*).

A number of the proposed schemes and elaborations were based on abstract assumptions or on purely superficial characteristics of soils, particularly their color. Such classifications disregarded an essential factor of soil genesis, the composition of vegetative cover, and are of little ecological or silvicultural value. On the other hand, many ecologically valuable contributions, made recently by students of forest soils, have thus far awaited consolidation. In this book an attempt is made, therefore, to arrange the available factual information into a simple universally-applicable classification, based primarily on ecological relationships.

The principles of climatic zonality, or "macro-zonality" have been supplemented by the more recent ideas of "micro-zonality" (WISSOTZKY, 1906; KRAUSS, 1911; KRUEDENER, 1926). Therefore, the influence of local soil-forming factors has been given particular emphasis. The theory of intra-zonality or endodynamomorphism has not been stressed. Typical representatives of endodynamomorphic soils, such as raw humus rendzinas, podzols on calcareous substrata, degraded prairie soils, and terra rossa, may well be regarded as climatic-zonal soils derived from a similar parent material. Likewise, the highmoors of mountains, acid bogs of the podozl region, sedge marshes associated with prairie soils, and tropical swamps in the lateritic region are as much a product of the zonal climatic and vegetational influences as the so-called "normal" soils of uplands.

A schematic outline of the proposed genetical classification of forest and associated soils is presented in Table 2. Representative profiles of upland forest soils are assembled in Plate 3.

TABLE 2.—*Genetic Groups of Forest and Associated Soils Classified on the Basis of Their Relation to Climate, Topography, Geology, Vegetation, and Ground Water:*—

Macro-Climatic Soil-Forest Zones	Degree of Leaching and Gleization of Soil as Determined by Combined Influences of Micro-Climate, Topography, Parent Material, Vegetation, and Ground Water Table			
	Mild leaching	*Strong leaching*	*Partial gleization*	*Complete gleization*
	Principal Genetic Types of Soils Formed in Each Zone			
MOUNTAIN SKELETAL SOILS; SUBALPINE FORESTS	mountain sod soils	mountain podzols	mountain soils influenced by seepage	highmoors
PODZOLIZED SOILS; BOREAL FORESTS: TAIGA AND NIGH-TAIGA	latent podzols; weakly podzolized soils or "mull soils"; rendzinas	podzols or strongly podzolized soils; calcareous podzols	podzolized gley soil; swamp podzols	muskeg; acid lowmoor peat
GROOD SOILS; PRAIRIE FORESTS OR DOOBRAVA	dark groods or slightly degraded chernozems	light groods or strongly degraded chernozems; podzolic soils	gley groods	alkaline marsh peat
MELANIZED SOILS; MESOPHYTIC FORESTS, ESP. HARDWOODS	melanized soils rich in bases; brownearths	melanized soils poor in bases; weakly podzolized soils	melanized gley soils	neutral or alkaline lowmoor peat
CHARRAL SOILS; SCLEROPHYLLOUS FORESTS	charral soils of calcareous substrata; terra rossa	leached charral soils; macchie soils	gley charrals	alkaline peat
LATERITIC SOILS (SIALLIZED); TROPICAL AND SUBTROPICAL RAIN FORESTS	humus-infiltrated lateritic soils	podolized lateritic soils; red and yellow podzolic soils	gley lateritic soils; lateritic podzols	acid tropical and sub-tropical peats
LATERITIC SOILS (FERRALLITIC); MONSOON AND SAVANNAH FORESTS	redearths rich in bases	leached redearths	indurated redearths; true laterites	alkaline tropical and sub-tropical peats

Podzolized Soils (Sesquioxide-Leached Soils):— Podzol is a Russian word meaning ash-like soil; it pertains to the color of the siliceous eluvial layer (SIBIRTZEV, 1900). The term "sesquioxide-leached soils" equally well expresses the nature of podzolized soils. In the out-moded, but entirely justifiable terminology of the old-time foresters, podzols were known as "raw humus soils" (SIGMOND, 1924). Raw humus, with all its complex chemical and biological influences, is the chief factor directly responsible for the translocation of sesquioxides and colloids, *i.e.,* the essential characteristic of the podzolization process (MÜLLER, 1878; EMEIS, 1908).

In the initial stage of podzolization, percolating water removes bases and other easily soluble substances from the surface soil layer. The resulting impoverishment in electrolytes, as well as winter freezing, inhibit the activity of microorganisms; consequently, plant remains accumulate on the surface as raw humus. Organic acids and reducing agents, such as hydrogen sulfide, are formed as by-products of the retarded decomposition. These derived organic compounds promote the dispersion and solubility of humus and cause reduction and other transformations which make possible the translocation of difficultly soluble iron and aluminum sesquioxides. The translocation of sesquioxides is further facilitated by the protective action of the humate colloids. At a certain depth the mobile colloidal suspensions are precipitated or flocculated because of electrostatic forces, subdued hydrolysis, or some other reasons as yet unknown. All of these transformations ultimately result in a soil profile of a mature or fully-

developed podzol consisting of a raw humus layer, an ash-like siliceous residue, and a reddish brown horizon with precipitated sesquioxides and humus (WITYN, 1924; GEDROIZ, 1929; MATTSON, 1933; DROSDOFF and TROUG, 1935).

The region of podzolization extends as a wide circumpolar belt throughout the northern parts of America and Eurasia (GLINKA, 1931). It is bounded by tundra on the north and grades into melanized and prairie-forest soils on the south. The boreal climate of this region is characterized by moist mild summers with equally distributed rains and cold winters with abundant snowfall. The vegetative cover consists of heath plants and many species of conifers and hardwoods. The stands on podzols and podzolized soils, referred to as "Tundra-Forest" or "Taibola", "Taiga", and "Near-Taiga", constitute the largest area of the world's forest. Under special conditions the process of podzolization penetrates in a southerly direction far beyond the podzol region proper and may affect the soils of other genetical groups. Podolized soils found in the tropics present an outstanding example of such a relationship (LANG, 1915; GIESECKE, 1930; SENSTIUS, 1930).

Depending upon the degree of podzolization, a number of morphological varieties or types are recognized, *viz.*, slightly leached or *weakly podzolized soils,* moderately leached or *podzolic soils,* and strongly leached soils or *podzols.* Concealed or *latent podzols* formed under heavy cover of grass, and *rendzinas* of calcareous deposits are further varieties of soils in the podzol region. All of these types are readily discernible in nature and have a decisive silvicultural importance (MOROZOV, 1930).

(1) *Weakly podzolized soils:* — These soils represent the embryonic stage of podzolization. In some instances, the absence of a pronounced leaching is a result of soil "youthfulness". As a rule, however, weakly podzolized soils are a more or less stable type, formed in localities where podzolization is inhibited by the high base content of the parent rock or by the litter of deciduous species. By and large, these soils are confined to the warmer portion of the podzol region.

In the weakly podzolized soils the layer of free organic remains (A_0), *i.e,* litter and duff, seldom exceeds a thickness of 2 inches. The horizon with incorporated humus (A_1) is well developed and imparts a dark color to the surface soil. The leaching is noticeable only upon a careful examination, and the A_2 and B horizons may not be apparent. A slightly acid or neutral reaction and a high biological activity are characteristic of these soils. The morphology of weakly podzolized soils may be exemplified by the following description of a profile formed under a stand of maple, basswood and elm in northern Wisconsin:

A_0 1.5 inches. Thin layer of undecomposed maple leaves covering a dark-brown nearly neutral friable duff having the pleasant odor of a good garden soil.

A_1 1.5-6 inches. Mull layer consisting of a slightly acid (*p*H 6.3) dark-grey crumbly loam; it is high in organic matter and it harbors earthworms.

A_2 Not present as a continuous horizon but small greyish spots reveal podzolization in the zone from 6 to 12 inches.

B Not discernible.

C Dark brownish-grey gravelly loam of a moderately acid reaction (*p*H 5.7), grading at a depth of 4 feet into unassorted glacial till. The roots penetrate throughout the entire profile to a depth of 7 feet.

Weakly podzolized soils are known under several other names: "mull soils", "dark forest soils" and "diorn soils". They may be regarded as the melanized soils of the north. The weakly podzolized sandy soils are referred to as "bor sands". In the majority of instances, weakly podzolized soils are correlated with the mixed stands of various hardwoods such as maple, basswood, beech, hornbeam, elm, ironwood, ash, and northern species of oak. Less frequently these soils support hardwoods mixed with spruce, fir, hemlock or pines. Forest cover composed entirely of conifers is largely confined to pines growing on sandy soils. The stands on weakly podzolized soils are apt to produce high yields of timber and regenerate readily by seeds and sprouts (Wilde and Scholz, 1934).

Weakly podzolized soils are the most productive agricultural soils of the podzol region and their use for forestry purposes is largely limited to rough and stony glacial deposits.

(2) *Moderately leached or podzolic soils:* — These soils exhibit a well-pronounced grey leached layer and a more or less distinct accumulative layer. The latter sometimes occurs in the form of concretions, "pseudomycelium", or slightly cemented "ortsand". Being a transitional form, podzolic soils have intermediate characteristics, partly derived from weakly podzolized soils and partly from true podzols.

Podzolic soils dominate the entire southern border of the podzol region; their distribution coincides closely with the occurrence of the broad zone of mixed hardwoods and conifers known as "near-taiga" (Belousov, 1921). The essential constituents of this silviculturally important zone in different parts of the world are as follows:

North America: — *Acer saccharum, Tilia americana, Fagus grandifolia, Betula lutea, Ulmus americana, U. racemosa, Fraxinus americana, Quercus borealis, Carpinus caroliniana, Populus tremuloides, P. grandidentata, Betula papyrifera; Tsuga canadensis, Thuja occidentalis, Abies balsamea, Picea glauca, Picea rubra, Pinus strobus, P. resinosa, P. banksiana, P. rigida; Tsuga heterophylla, Thuja plicata, Abies grandis, Picea engelmannii, P. sitchensis, Pseudotsuga douglasii, Pinus monticola, P. contorta, Larix occidentalis.*

Europe: — *Quercus sessiliflora, Q. pedunculata, Fagus silvatica, Tilia parvifolia, T. grandifolia, Fraxinus excelsior, Acer platanoides, Ulmus campestris, U. effusa, Carpinus betulus, Alnus incana, Betula verrucosa, Populus tremula; Abies pectinata, Picea excelsa, Pinus silvestris.*

Asia: — *Quercus mongolica, Tilia manshurica, Acer manshuricum, Fraxinus manshuricum, Ulmus spp., Populus suaveolens, P. tremula, Betula verrucosa, B. pubescens; Tsuga dumosa, Abies siberica, A. nephrolepis, A. pindrau, Picea obovata, P. ajanensis, Pinus cembra, P. sinensis, P. manshurica, P. koreensis, Larix siberica, L. griffithii, L. dahurica.*

Dairy farming is the principal agricultural enterprise on podzolic soils. Winter rye, barley, oats, and potatoes are the chief field crops. Fruit-growing is locally of considerable importance.

(3) *Strongly leached soils or podzols:* — True podzols are characterized by a thick layer of undecomposed organic matter or raw humus (A_0), the entire absence or only slight development of the melanized layer (A_1), an ashy-grey or white leached layer (A_2), and a sharply defined reddish-brown

cemented or compacted accumulative layer (*B*). The amount of salts extracted with 10 per cent HCl is two to three times as large in the *B* layer as in the A_2 layer. The A_2 layer in some cases contains as much as 95 per cent of silica. The available nutrients are concentrated in the raw humus layer. The exchange material is saturated chiefly with hydrogen ions and is subject to destruction in the entire soil profile (GEDROIZ, 1929). Insect life is often absent. The bacteria are largely replaced by the acid-loving fungi (WAKSMAN, 1938).

The following is a description of a typical podzol profile, developed under a stand of hemlock, balsam fir and yellow birch in northern Wisconsin:

A_0 4 inches. Layer of raw humus, or mor, consisting of strongly acid (*p*H 4.0), matted, dark-brown organic remains penetrated by fungous mycelia, and giving off a peculiar "sour" odor. Line of demarkation between organic matter (A_0) and mineral soil (A_2) is sharply defined.

A_1 Not present.

A_2 4-16 inches. Light grey nearly white sand with irregular tongue-like lower limits, strongly acid (*p*H 3.8).

B_1 16-27 inches. Slightly cemented sandy loam of a coffee-brown, somewhat reddish color (Ortsand).

B_2 27-45 inches. Firmly cemented, rock-like hardpan layer of a dark coffee-brown color, strongly acid (*p*H 4.0), and free of tree roots (Ortstein).

C Stratified sand.

The hardpan layers of mature podzols sometimes attain a thickness as great as 4 feet. Depending upon the proportions of iron and humus in the B horizon, podzols are classified into "iron podzols" and "humus podzols" (RAMANN, 1911; FROSTERUS, 1914). The development of the latter type is correlated with the occurrence of highly acidophilous vegetation, impeded drainage, and a particularly thick layer of raw humus (TAMM, 1920). In heavy soils podzolization develops sticky and mottled "claypan" layers similar to gley horizons formed by ground water. The soils of this nature do not differ greatly in their ecological effects from poorly drained soils, and are sometimes classified as "gley podzols." In this way podzolization may produce poorly drained soils on uplands far above the real water table.

The region of podzol soils coincides with the "taiga" forest composed chiefly of conifers, *viz.*, spruce, fir, hemlock, pines and larch. The occurrence of deciduous species is limited to aspen, poplars, birch, alder, mountain ash, and willows. The most important species inhabiting the podzol soils of the northern hemisphere are listed below:

North America: — *Tsuga canadensis, Abies balsamea, A. hudsonica, Picea glauca, P. mariana, P. rubra, Pinus strobus, P. banksiana, P. rigida, Larix laricina, Betula lutea, B. papyrifera, B. alaskana, Populus tremuloides, P. grandidentata; P. candicans, P. balsamifera, Tsuga heterophylla, T. mertensiana, Thuja plicata, Abies lasiocarpa, Picea engelmannii, Pinus contorta, Larix lyallii.*

Europe: — *Picea excelsa, Pinus silvestris, P. lapponica, Larix europea;* species of *Sorbus, Alnus, Betula, Populus,* and *Salix.*

Asia: — *Abies sachalinensis, Abies siberica, Picea obovata, P. bicolor, P. ajanensis, Pinus siberica, P. cembra, Larix siberica, L. dahurica, L. kurilensis,* species of *Sorbus, Alnus, Betula, Populus,* and *Salix.*

Under natural conditions, the stands on podzol soils attain a fair and even a high productivity. However, in reforestation the growth of planted trees may be hindered by a strongly acid reaction, lack of plant food in the leached layer, toxicity of the accumulative layer and its unfavorable effect on the distribution of moisture during wet and dry seasons. The cementation or the toxicity of the accumulative layer leads to the development of a superficial root system and trees on podzol soils are subject to windfall (Albert, 1912; Weis, 1929; Stickel, 1929; Lutz, 1934; Mařan, 1938).

Table 3. — *Total analysis of a weakly podzolized loam supporting a stand of hard maple, basswood and associated hardwoods, and of a sandy loam hardpan podzol supporting hemlock, yellow birch and balsam fir. Terminal moraine in Langlade County, Wisconsin.* (S. A. Wilde and S. F. Buran): —

Soil Constituents	Weakly podzolized soil			Hardpan podzol		
	A_1 0-6 in.	A_2B 12-24 in.	C 36-48 in.	A_2 4-12 in.	B 24-36 in.	C 44-52 in.
	Per cent			Per cent		
N	0.27	0.05	0.01	0.02	0.06	Tr.
SiO_2	64.52	71.93	73.46	79.03	69.02	75.47
Fe_2O_3	2.82	2.35	2.02	1.31	4.10	2.98
Al_2O_3	11.24	12.71	11.97	9.77	14.05	11.12
TiO_2	1.02	1.63	1.34	0.71	2.07	0.98
CaO	2.83	1.78	2.94	0.44	1.79	1.73
MgO	1.53	0.63	0.91	0.48	0.74	0.64
K_2O	2.10	1.02	2.93	1.71	2.40	2.43
P_2O_5	0.29	0.14	0.32	0.01	0.64	0.20

Areas of true podzols are primarily forest lands as their fertility is rapidly depleted by clearing and decomposition of the raw humus layer.

Table 3 includes the results of total analysis of a weakly podzolized soil and a fully developed podzol.

(4) *Latent podzols:* — The podzols and podzolic soils of old cut-over areas and forest meadows may be "masked" by the infiltrated grass humus which imparts a dark color to the whole soil profile. Although the leached layer is not readily discernible in such soils, the podzolization is often manifested by the cementation of the B horizon, or it may be revealed by chemical analysis. Soils of this kind are called *latent podzols* (Glinka, 1931). On superficial examination they resemble the weakly podzolized soils.

In the proximity of tundra, latent podzols occupy extensive areas side by side with swamp podzols and muskeg bogs. The forest cover of this tension zone of the north acquires a distinct character of interrupted tundra-forest and is referred to in some writing as "taibola" (Pohle, 1904). It consists largely of larch and spruce with some birch, poplars, alder, and mountain ash. There is only a slight difference in the floristic composition of this forest type along the entire circumpolar timber line. The appearance and low productivity of the forests of the taibola or "polaretum" resemble those of the high mountain regions or "alpinetum" (Mayr, 1909). The sod soils of high mountains may be regarded as a variety of latent podzols.

(5) *Rendzinas:* — Calcareous parent material modifies the common course of the podzolization process and gives rise to a peculiar variety of

soils called rendzina (MIKLASZEWSKI, 1922; NIDA, 1932). These soils occur sporadically throughout the entire podzol region, being confined to areas of outcropping limestone, dolomite, chalk, marl, lime-bearing shales, and calcareous glacial deposits. A high content of either incorporated or raw humus is the outstanding feature of rendzinas which well justifies their other accepted designation — *humus-calcareous soils* (GLINKA, 1931). In the earlier works, rendzinas were considered "endodynamomorphic" or "endodynamogenic" soils reflecting chiefly the composition of the parent material rather than climatic factors. With the advance of knowledge, however, it became apparent that soils of calcareous rocks or deposits are subject to the same changes as soils of any other parent material, and hence the profile of rendzinas gradually attains the morphology of podzolized soils (LEBEDEV, 1906; ZVORYKIN, 1929). The lower the content of carbonates in the parent material, the sooner a humus-calcareous soil is transformed into its regional genetic or climatic-zonal type. The degree of humidity and the amount of percolating water also play an important part in the rapidity of leaching or "degradation" of rendzinas.

In the region of true podzols, exposed calcareous rocks encourage an accumulation of peat-like raw humus with an alkaline reaction, attaining a thickness of nearly one foot (GALLOWAY, 1940). Such youthful rendzinas, in spite of their alkaline reaction, often support acidophilous species of spruce and fir, in addition to white cedar and hardwoods (TKACHENKO, 1911; LANG, 1935). In time the calcareous material undergoes weathering and leaching, and is transformed into a *calcareous podzol* or, rather, a podzol of calcareous substratum (SEE, 1921). In the proximity of the Great Lakes, such calcareous podzols often have strongly acid ortstein layers which rest upon alkaline, calcareous detritus (WILDE, 1932*b*).

In the prairie-forest transition, rendzinas undergo a more complex sequence of changes. In such regions the initial stage of rendzina development is a skeletal calcareous debris, darkened by infiltrated humus, and giving effervescence with strong acids. As weathering proceeds, the upper layer of the rendzina loses its carbonates; the residue becomes smooth and silty in texture and develops a deep, dark or black humus horizon having a crumby structure. At this state rendzina soils are often similar to black-earth; they support prairie vegetation and are referred to as *prairie soils* (MARBUT, 1935). After invasion of forest vegetation, the rendzinas undergo degradation similar to that of chernozems and eventually attain the profile of a grood or podzolic soil (ZVORYKIN, 1929; CHAVANNES, 1940). Figure 6, adapted from LEBEDEV (1906), shows four stages in the development of a rendzina.

The forest cover of rendzinas is highly diversified and includes many lime-tolerant or caliphilous species, such as oaks, hickory, walnut, beech, ash, juniper, and white cedar. However, all trees on rendzinas suffer from malnutrition due to the high content of carbonates. The stands show a very low rate of growth, high percentage of cull, and are subject to premature death; their natural regeneration is often handicapped by the absence of mycorrhizal organisms as well as by the attacks of damping-off fungi (WHITE, 1941; ROSENDAHL, 1943). The rate of growth and the general

stability of the forest on these soils increase with the accumulation of forest debris and the advance of podzolization.

Grood Soils (Nut-Structured Prairie-Forest Soils): — Near the humid boundary of the steppe, the invasion of the forest initiates the leaching or "degradation" of blackearth soils. In time this process leads to the development of transitional *prairie-forest* or *grood soils.*

"Grood" is a folk term that has been adopted by forest pedologists (KRUEDENER, 1927; MOROZOV, 1930) as a substitute for earlier synonyms, such as "nut-structured soils", "grey forest soils" (KORZHINSKY, 1891; SIBIRTZEV, 1900) and "degraded soils" (GLINKA, 1931). It refers to the structural aggregates characterizing the profile of prairie-forest soils, as

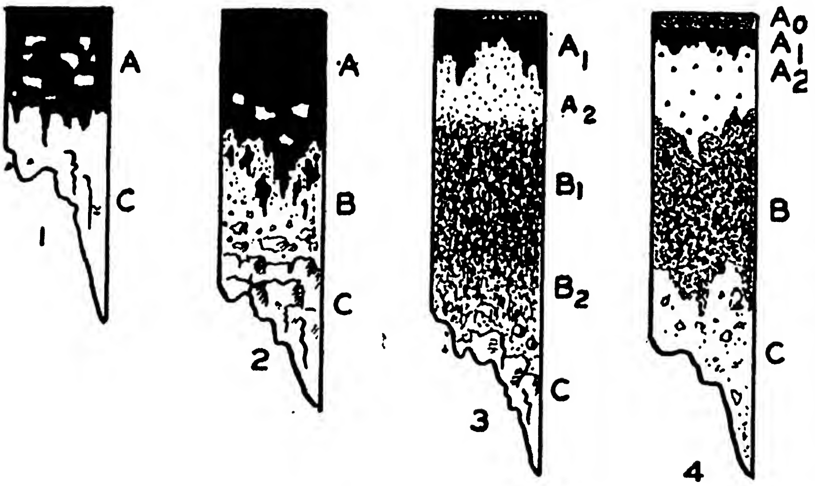


FIGURE 6. — Metamorphosis of rendzina into podzolic soil: 1. Immature skeletal rendzina; 2. Fully developed rendzina; 3. Degraded rendzina; 4. Podzolized rendzina or podzolic soil with calcareous substratum. (*After* LEBEDEV).

well as the type of forest cover which these soils support, *i.e.,* a type distinctly different from the associations of podzolic soils (POGREBNIAK, 1931; WILDE, 1940*a*). KRUEDENER (1927) makes the following statement in his "Waldtypen": "Rural people in their efforts to enlarge the agricultural area, very well appraised the differences in productivity of the grood and podzol types." (p. 82). In American literature, grood soils were described under the names of "grey-brown podzolic soils" (BALDWIN, 1928; MARBUT, 1935; KELLOGG, 1936), "grey forest soils" (JOFFE, 1936), and "degraded chernozems" (U. S. D. A. 1938).

The forest invading chernozems or prairie soils (KORZHINSKY, 1891) raises the humidity, moderates evaporation, and retards the melting of the snow, thus increasing the amount of water which percolates through the soil profile. The accumulated forest litter promotes the formation of reducing agents and organic acids which break down both the humate and iron-aluminosilicate fractions of the base exchange compounds. In consequence, the humus is gradually removed from the upper layer, which attains a lighter color (KRAVKOV, 1912). As Russian farmers say, "The forest devours

the chernozem." The released silica appears in the profile as white dust or "frosting." The iron and aluminum sesquioxides accumulate as a brownish precipitate in the lower layer and give the degraded chernozem the appearance of a true forest soil with distinct humus, leached, and accumulative horizons (TKACHENKO, 1908; GORSHENIN, 1924; FLOROV, 1925; TUMIN, 1930).

The peculiar characteristics of the *continental climate* of the prairie-forest belt, *i.e.* cold winters, but hot and dry summers, appear to be of major importance in the development of grood soils. Cold winters with lasting snow cover periodically inhibit the activity of microorganisms and promote the accumulation of organic remains in quantity sufficient to effect the translocation of sesquioxides, *i.e.*, a process nearly as vigorous as true podzolization. At the same time the percolation of water is not sufficiently deep to remove carbonates from the lower strata (WISSOTZKY, 1930).

In the initial stages of development, grood soils are designated as "degraded chernozems", "degraded prairie soils", or *dark groods.* Such soils, as a rule, are found in the proximity of the prairie and have a high content of humus, exceeding 5 per cent. Their morphology and chemical composition resemble those of the blackearth soils (ZAKHAROV, 1931). On the other hand, *leached* or *light groods* contain from 2.5 to 5.0 per cent of incorporated humus. Their eluvial layer is of a grey or greyish-tan color and has a platy structure, typical of podzolic soils. It grades into a brown accumulative horizon which in fine textured soils has a peculiar nut-structure. The structural aggregates are covered with siliceous dust. The accumulative horizon is underlain by a zone containing carbonates of calcium and magnesium. The reaction of the upper soil layers is acid, the reaction of the lower part of the B horizon and of the substratum is commonly neutral or alkaline. The following description outlines the morphological features of a leached grood profile, developed under an oak-hickory stand in northeastern Iowa.

A_0 Undecomposed oak leaves, acorns, twigs, and other forest litter varying in thickness from 1 to 2 inches.

A_1 0-6". Dark grey silt loam high in organic matter and of a slightly acid reaction (*p*H 6.5), mellow and smooth to the touch, breaking into fine aggregates. It contains a considerable number of small earthworms and is penetrated by a network of roots. Lower limit of horizon is irregular with tongues and root channels extending into the lower portion of the profile.

A_2 6-14". Light grey to tan, brittle silt loam showing a distinct platy structure with strata of 1/16 to 1/32 of an inch in thickness. Plates are "frosted" with siliceous dust. The reaction is acid (*p*H 5.6). Roots are numerous and some earthworms are present.

A_2B 14-20". Light chocolate-brown porous silt loam breaking into small nut-like aggregates about the size of a pea, showing a gray or white speckled coating. Nuts are honey-combed by a number of very fine channels.

B_1 20-32". Chocolate brown silty clay loam breaking into larger aggregates about the size of a small acorn and exhibiting porous structure and greyish siliceous powder when dry. Penetrated by tree roots and with some large earthworms in root channels. Acid (*p*H 5.8).

B_2 32-48". Reddish-brown clay loam with rusty streaks. Contains some carbonates and exhibits a tendency to break into large cloddy aggregates in the upper portions of the horizon. Reaction is alkaline (*p*H 7.8). Some fine roots are present.

C 48" plus. Calcareous detritus terminating the distribution of roots.

Table 4 reports results of total analysis of a grood silt loam. Both the profile descriptions and analytical data of American grood soils are applicable to similar soils of Eurasia (KASSATKIN and KRASIUK, 1917; LEVCHENKO, 1930; TIURIN, 1930).

TABLE 4. — *Total Analysis of a Nut-Structured Grood Loam Formed Under a Stand of Oak and Hickory in Southern Wisconsin* (S. A. WILDE and D. P. WHITE): —

SOIL CONSTITUENTS	A_1 0-4 in.	A_2 4-12 in.	B_1 16-24 in.	B_2 36-48 in.	C 56-60 in.
	Per cent				
N	.30	.04	.03	.015	.003
SiO_2	73.03	78.74	71.40	64.98	76.12
Fe_2O_3	2.23	2.47	4.27	4.71	2.17
Al_2O_3	8.34	8.94	10.12	11.90	8.28
TiO_2	.401	.367	.474	.495	.393
MnO	.143	.077	.087	.164	.231
CaO	.981	.692	.930	1.472	1.850
MgO	.624	.127	.632	.953	1.245

In time the leaching may remove most bases from the B horizon, destroy structural aggregates, and thus convert a grood soil into a podzolic soil. In some instances grood soils are invaded by the prairie grasses and undergo melanization or "regradation", *i.e.*, a process opposite to leaching, and resulting in the transformation of groods into chernozems or prairie soils (GLINKA, 1931).

Grood soils support stands of oak, hickory, and walnut with some ash, elm, maple, basswood, and other hardwoods occurring incidentally. The oaks play a part of undisputable predominance in this extensive and distinct type of forest, referred to in Russian as "doobrava" (MOROZOV, 1930). In the proximity of prairie, hardwoods are sometimes replaced by the so-called "poplar savannah" and pioneer stands of white birch. In the extremely continental climates of Siberia and Canada, spruce and other conifers occur incidentally in the transitional belt of grood soils. The following list covers outstanding tree species of American and European grood soils:

North America: — *Quercus alba, Q. borealis, Q. velutina, Q. macrocarpa, Carya ovata, C. cordiformis, C. alba, Juglans nigra, Acer negundo, A. saccharum, Tilia americana, Celtis occidentalis, Fraxinus lanceolata,* species of *Prunus, Populus,* and *Salix; Juniperus virginiana.*

Eurasia: — *Quercus pedunculata, Q. sessiliflora, Juglans regia, Fraxinus excelsior, Acer negundo, Acer platanoides, A. campestre, Tilia parvifolia, T. grandifolia, Carpinus betulus, Ulmus effusa,* species of *Populus, Betula, Prunus,* and *Salix; Juniperus communis.*

The native forest stands on grood soils usually have short boles, poorly shaped stems, high percentage of cull, and often inferior stocking. The yields seldom exceed 7,000 board feet per acre (WILDE, 1940*a*). The productivity of stands is especially low near the border of the blackearth, but it increases toward the podzol region where leaching of the soil is greater and carbonates are removed to a greater depth in the soil profile. By and

large, groods are highly productive agricultural soils; intensively managed woodlots are about their only justifiable silvicultural use. The greatest portion of the grood soils is utilized at present for the production of corn or spring wheat (KLAGES, 1942).

Melanized Soils (Humus-Incorporated Soils): — Melanized soils may be regarded as the blackearths of the forest (SCHLICH, 1910). Their name was derived by the writer from the Greek "melas", "melanos" meaning black or dark. The profile of these soils is composed of a dark surface layer with incorporated "mull" humus and apparently undifferentiated or unaltered substratum. The expression "black top soils" would outline the general appearance of melanized soils.

This soil group is confined to a transitional climatic zone where neither podzolization nor laterization are manifested in the soil profile, *i.e.*, where there is little translocation of either sesquioxides or silica. Thus, the leaching in these soils is largely limited to the easily soluble sulfates and carbonates which accumulate in varying amounts in the deeper part of the substratum. A considerable portion of these compounds is returned to the surface layer by vegetation and soil organisms. As a consequence, melanized soils present a unique example of a profile in which nearly all of the constituents are more or less fixed "in situ". This morphological equilibrium of soil is sponsored by mild *oceanic climate* with its moist, warm summers and mild winters with sporadic snow cover. The native vegetation of hardwood species is an additional contributing factor (STEBUTT, 1930).

The dark humus horizon (A_1) of melanized soils gradually becomes lighter in color and merges into the parent material (C). Therefore, the differentiation of these soils into A, B, C horizons is difficult. Such a differentiation may be justified, however, when the translocation of bases (CaO, MgO, K_2O and Na_2O) is detected by means of chemical analysis.

The following description gives an example of a characteristic soil profile.

A_0 Sparse interrupted remains of the last year's leaf fall.

A_1 0-16". Dark brown crumby humus loam growing lighter with depth; somewhat compacted and penetrated by light colored veins and threads in the lower portion. Nearly neutral in reaction.

C 16-42". Reddish brown compacted clay loam of a slightly alkaline reaction, penetrated by the roots of trees and root channels, and underlain by disintegrated shale.

Table 5 presents data of profile analysis of a melanized soil from southern Indiana. Table 6 adapted from MARBUT (1935), includes data on a genetically related soil from Massachusetts. The uniformity in the distribution of mineral constituents makes it evident that both soil profiles are at a state of equilibrium.

Melanized soils are closely related to the "brownearth", described by RAMANN (1918), but not identical with that type. According to recent investigations, the concept of "Braunerde" or "brown forest soils" is applicable to a number of soil groups, *viz.*, weakly podzolized soils, latent podzols, lateritic soils, and even degraded chernozems. This confusion arose chiefly because RAMANN gave only vague descriptions of the soil type he introduced as the brownearth (STREMME, 1930). To some extent, the matter was complicated by unfortunate terminology: the "brownearth" includes soils of various colors other than brown, and, conversely, many brown soils are not related to the

TABLE 5. — *Total Analysis of a Melanized Loam Supporting a Stand of Hardwoods in Southern Indiana* (S. A. WILDE and W. E. PATZER): —

HORIZON AND DEPTH	N	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	K_2O	P_2O_5
	Per cent									
A_1: 0.-8 in. ...	.221	73.51	3.28	8.27	.32	.59	1.61	.59	1.04	.11
A_1-A_2: 8-16 in.	.073	77.80	3.47	8.15	.35	.47	.96	.47	.87	.09
A_2B: 16-30 in.	.041	82.05	3.46	8.29	.33	.45	.88	.46	.75	.12
C: 30-40 in...	.006	82.20	4.01	7.49	.33	1.06	1.73	1.06	1.18	.08

TABLE 6. — *Total Analysis of a Merrimac Fine Sandy Loam from Foxboro, Massachusetts* (C. F. MARBUT and F. A. BAKER): —

HORIZON AND DEPTH	N	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	K_2O	P_2O_5
	Per cent									
A_1: 0-2.5 in....	.35	64.78	4.31	11.41	.99	.06	1.33	.66	1.16	.24
A_2: 2.5-3.5 in...	.43	64.15	3.83	9.93	.97	.06	1.02	.71	1.14	.31
B: 3.5-18.0 in...	.15	69.17	4.41	12.85	.89	.06	1.40	.77	1.11	.39
C: 18.0-28.0 in.	.09	72.89	4.25	11.60	1.05	.07	1.57	.91	1.22	.15

brownearth. All things considered, the term brownearth has become more a liability than an asset and the revision of its concept, as well as the change in designation, is highly desirable. The terms "humus-incorporated" or "melanized" soils appear to imply best the original, basically correct ideas of RAMANN on the genesis of soils formed in milder climates of the temperate zone and characterized by the dark layer of humus.

The absence of pronounced eluvial and illuvial horizons induced some scientists to classify humus-incorporated soils as immature soils with "imperfectly developed profiles" (MARBUT, 1935). The predominance of "undifferentiated" melanized soils in central Europe was responsible in a large degree for the failure of the earlier soil scientists to recognize the role of climate in soil development. Instead they emphasized the importance of the parent material (FALLOU, 1862; GREBE, 1886) which indeed greatly influences the properties of melanized soils.

Being a transitional group, melanized soils exhibit a great deal of variation in color, structure, and chemical composition. Near the podzolic boundary, the surface layer of melanized soils is often characterized by greyish or grey-brown shades. In the proximity of the lateritic boundary, the profile of melanized soils is somewhat enriched in iron, and attains an intensive brown, reddish-brown, or chocolate-brown color; these are among the most impressive shades exhibited by soils. The color of the lower portion of melanized soils is also affected by the nature of parent material. Under the hardwood stands of Central Europe, particularly in Bohemia and on the southern foothills of the Carpathians, are found melanized soils which in their color and crumbly structure are comparable to true blackearths; these features of melanized soils appear to coincide with the occurrence of basaltic and related ferro-magnesian parent materials.

Depending upon parent material and other conditions, melanized soils may be either poor in bases and distinctly acid in reaction, or rich in bases and nearly neutral or alkaline in reaction. Both varieties occupy considerable continuous areas, or occur intermittently, forming a mosaic. In regions with heterogeneous geologic substrata, the distribution of base-saturated

and base-unsaturated melanized soils presents an especially mottled pattern. Aside from the influence of parent rock, the degree of base saturation is influenced by the topography and the composition of forest cover. A higher content of bases is often found on the lower slopes. Oaks seem to exert a greater leaching effect than other hardwoods. The development of soil aggregates is correlated with the degree of base saturation. In most instances, base-saturated melanized soils have a granular structure distinctly different from the nut-structure of grood soils (MURGOCI, 1909). According to the writer's experience with soils of Central Europe, the brownearths of RAMANN are confined to lime-bearing substrata, and should be identified as melanized soils rich in bases. The "brown podzolic soils" and "brown forest soils", described by BALDWIN, KELLOGG and THORP (1938), appear to correspond to acid and circumneutral varieties of melanized soils.

The melanized soils of central Europe, eastern portions of the United States, China, and numerous belts of the lower mountain slopes throughout the world constitute approximately one-tenth of the total area of forest soils. In general, these soils have a high content of base exchange material and available nutrients. They support highly productive stands composed primarily of mesophytic hardwoods, among which tulip poplar, beech, chestnut, maple, walnut, hickory, and species of oak are prominent. The occurrence of conifers is limited to a few megathermic species. The "Central" or "Southern" hardwoods of eastern America (SHANTZ and ZON, 1924) and the "Fagetum-Castanetum" of Europe (MAYR, 1909) constitute the silviculturally prominent associations on melanized soils. The forests on these soils are characterized by the abundant production of mast, consisting of chestnuts, acorns, beechnuts, walnuts, and the nuts of hickory and other species. Consequently the expression "hardwood mast forest" may be applicable to this broad forest type. The floristic composition of these forests is outlined by the following list of species:

North America: — *Castanea dentata, Liriodendron tulipifera, Quercus montana, Q. alba, Q. rubra, Fagus grandifolia, Juglans nigra, J. cinerea, Carya alba, C. cordiformis, Platanus occidentalis, Aesculus spp., Fraxinus americana, Acer saccharum, Tilia glabra, Robinia pseudoacacia, Gleditsia triacanthos, Magnolia acuminata, Oxydendrum arboreum, Gymnocladus dioica.*

Europe: — *Castanea vesca, Quercus pedunculata, Q. sessiliflora, Q. cerris, Q. hungarica, Fagus silvatica, Carpinus betulus, Fraxinus excelsior,* species of *Acer* and *Ulmus*.

Asia: — *Castanea crenata, Liriodendron chinensis, Gymnocladus chinensis, Quercus serrata, Q. variabilis, Q. glandulifera, Q. dentata, Zelkova keaki, Phellodendron amurense, Ailanthus glandulosa,* species of *Juglans, Fraxinus, Acer, Ulmus, Celtis, Aesculus,* and *Gleditsia*.

According to American records, the hardwood stands on melanized soils attained a record productivity of 30,000 to 40,000 board feet per acre. During the past century, a number of microthermic conifers, such as Norway spruce and European larch, were introduced on melanized soils in central European countries. However, neither climatic conditions nor the properties of the soil proved to be satisfactory for these species. The introduction of conifers produced, in numerous cases, a rapid leaching of soils and their

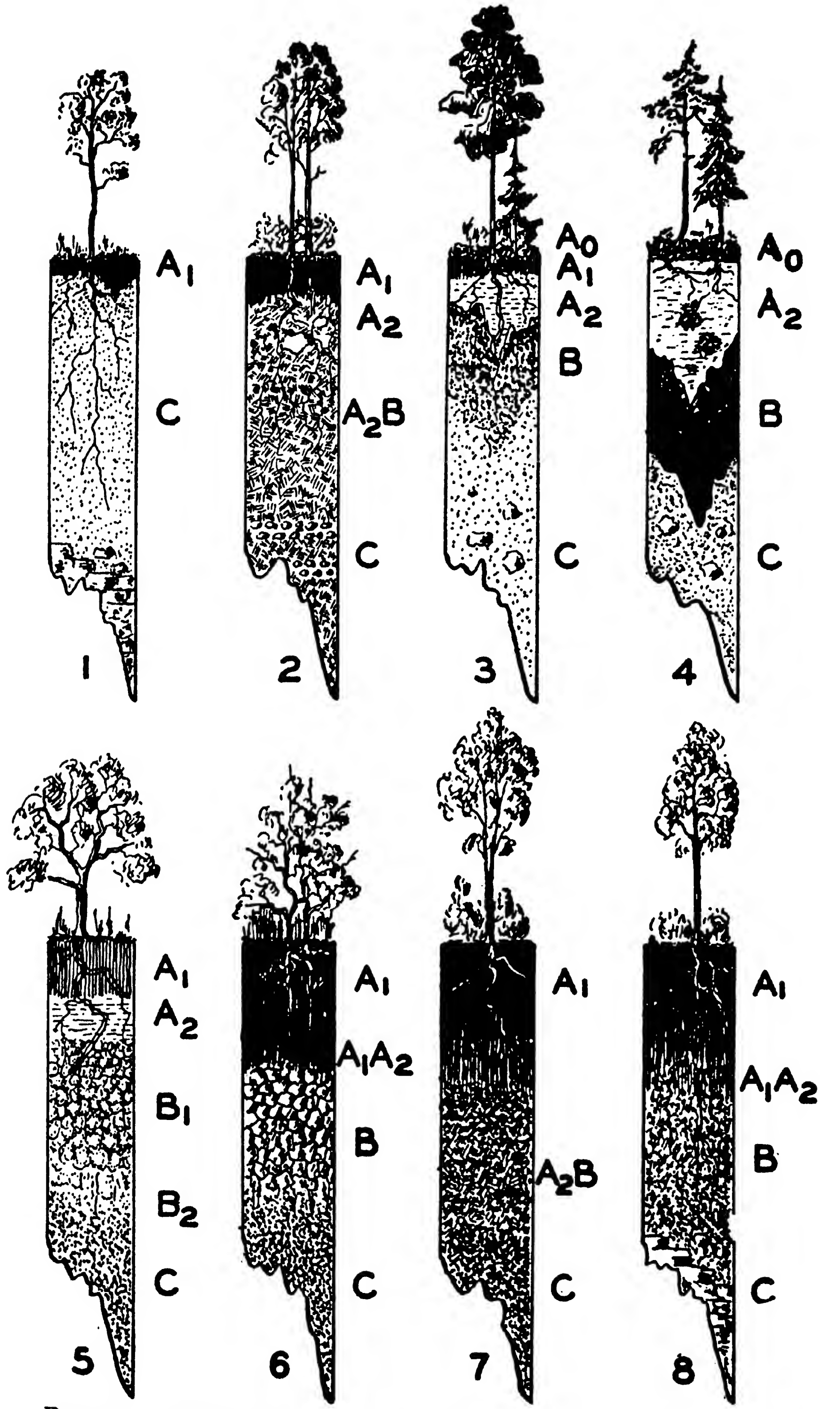


FIGURE 7. — Representative profiles of important upland forest soils of the temperate zone: 1. Embryonic soil; 2. Weakly podzolized soil; 3. Podzolic soil; 4. Podzol with hardpan horizon; 5. Leached grood or strongly degraded chernozem; 6. Dark grood or slightly degraded chernozem; 7. Melanized soil rich in bases with faintly differentiated horizons, or "brownearth"; 8. Melanized soil poor in bases, approaching weakly podzolized soil.

conversion into podzolized soils or even true podzols. The silvicultural significance of such a transformation is not well established; one group of foresters is inclined to see in podzolization the beneficial modification of environment, favoring the growth of planted conifers, while another group identifies podzolization with the deterioriation of soil fertility (SIGMOND, 1930; ERDMANN, 1930; LEININGEN, 1931).

From an agricultural viewpoint, the melanized soils constitute a region that produces winter wheat, corn, hemp, hops, tobacco, grapes, and fruits.

Figure 7 presents in a schematic form the profiles of the principle genetic types of upland forest soils of the temperate zone.

Lateritic Soils (Soils of Sesquioxide-Enriched Substrata): — The high temperatures of tropical regions bring about an intense chemical decomposition of the majority of minerals. In some cases, even the most resistant silicate compounds are broken down so that silica and hydrated oxides of iron and aluminum are set free. Under the influence of rainfall bases are washed out; silica is also partly removed by the drainage waters, whereas oxides of iron and aluminum accumulate as residue. As a result, residual parent materials in tropical regions are characterized by a low silica-sesquioxide ratio, usually less than 2, and by a high content of colloids. The accumulated iron imparts to the weathered material a striking red or yellow color. These changes take place in the surface layers, as well as at a depth of scores of feet (LANG, 1914; HARRASSOWITZ, 1926; WIEGENER, 1929; I. B. S. S., 1932).

The end product of tropical weathering was designated by BUCHANAN (1807) as *laterite*. The name was derived from the Latin *later* meaning brick, because strongly weathered and hardened clays were used in India as building stone. In the course of time the term *laterite* has been given various interpretations (SHANTZ and MARBUT, 1923). It has been applied to geological strata, ferruginous crusts, tropical soils in general, to all red soils, and to soils of a low silica-sesquioxide ratio. Recently, laterite was identified with *allite* (HARRASSOWITZ, 1926), *i.e.*, weathered products enriched in aluminum oxide and impoverished in silica; the allite was contrasted with *siallite,* a product containing both silica and alumina in a fairly balanced ratio. In this book the use of the term *laterite* is restricted to the end product of tropical weathering in its extreme form, *i.e.*, an indurated residue of iron and aluminum oxides. The term *lateritic,* on the other hand, is used in a very broad sense to designate the strongly hydrolyzed ferrallitic *parent materials* of tropical or subtropical regions; consequently, the term covers substrata of different petrographic origins and rather wide silica-alumina or silica-sesquioxide ratios.

Laterization is a geological rather than a soil-forming process; it penetrates far beyond the layer of the earth's surface that serves as a medium for plant growth. Once formed, the products of laterization are very stable, remaining unchanged for a time that can only be measured by a geological scale. Many soils of the present temperate region are underlain by lateritic beds which are regarded as fossil deposits (GLINKA, 1931).

From an ecological standpoint it is very important that the establishment of the climax tropical forest takes place upon already laterized sub-

strata, that is, red residue impoverished to varying degrees in bases and silica. After the succession of the pioneer grasses and shrubs is completed and the forest is established on a "ferrallized" weathered material, or an "immature redearth", laterization may proceed at the same or a somewhat slower rate (savannah forest); it may be arrested; or it may be replaced by the diametrically opposed process of podzolization (rain forest). In the first instance, the soil-forming process will culminate in a strongly allitic and indurated redearth, or "true laterite"; in the latter case, the climax is a deferrallized or siallitic podzol. It is obvious that the time factor of DOKUCHAEV plays a particularly vital part in the genesis of tropical soils and in their adaptation to plants.

The soils developed from lateritic material have, by and large, a heavy texture and a considerable depth; the inherited deficiency of alumino-silicate compounds greatly decreases their absorbing or base exchange capacity. In many instances the retention of water and nutrients is still further reduced by a nearly complete decomposition of organic matter. As the result, lateritic soils have a very low content of exchangeable cations and their fertility depends largely upon the supply of weatherable minerals. The reaction is influenced by conditions of climate, floristic cover, and age of the soil; it varies from mild alkalinity to extreme acidity. Some generalized classifications considered lateritic and podzolic soils as being two members of the same family of "pedalfers" (MARBUT, 1935), or "unsaturated soils" (GEDROIZ, 1929), with a "disintegrating exchange compound" (STEBUTT, 1930). However, the relationship between these two groups is merely superficial. From the standpoint of plant nutrition, laterization is a much more destructive process than podzolization; under extreme conditions it leads to the development of solid ferrallitic crusts precluding the growth of any form of vegetation (ROBINSON, 1932). With few exceptions, the nutritional and cultural aspects of lateritic and podzolized soils have little in common.

The soils formed on lateritic substrata support several broad types of the world's forests, *viz.*, tropical, subtropical, and temperate rain forests, monsoon forest, savannah woodland, thorn forest, and sclerophyllous or "leatherleaf" forest. Thanks to the work of plant geographers, especially DE CANDOLLE, GRIESEBACH, and SCHIMPER, there exists, at present, a comprehensive and well organized body of knowledge on the forest vegetation of the tropics. However, the knowledge of tropical soils and of their relation to plants is extremely fragmentary. Soil scientists have paid, thus far, amazingly little attention to the floristic features of tropical soils. Many voluminous works on lateritic soils leave the reader in complete ignorance as to the composition of the native vegetation and the state of ecologically important soil factors, such as water cycle, type of humus, reaction, and content of nutrients. Instead many pages are devoted to unrelated descriptions of profiles and merely coincidental features or constituents of the soil. How much more useful to foresters, agronomists and horticulturists many pedological reports would be if their authors had taken the trouble to page through SCHIMPER's monograph or a similar work. The book by VAGELER (1933) is one of a few exceptions, which in a large measure enabled the writer to devise a general outline of the forest soils of tropical regions.

At the present state of knowledge, only a very general correlation can be drawn between the composition of forest cover and the nature of soils in the greatest portion of the region affected by laterization. The most important soil-forest units are: (a) *Redearths* or *ferrallitic soils*, including *redearths* proper, *indurated redearths* (true laterites), and *leached red-*

earths; these are correlated with the occurrence of periodically-dry savannah woodland, thorn forest, and monsoon forest; (b) *Charral soils,* embracing several petrographic varieties of the soils of subtropical subhumid regions occupied by sclerophyllous forest; (c) *Humus-enriched lateritic soils* with either apparent or concealed humus horizons, and (d) *Podzolized lateritic soils;* both of these groups of *siallitic* nature support tropical and subtropical rain forests. Figure 8 based on the Brockmann-Jerosch's (1919) outline of an ideal continent, presents schematically the distribution of lateritic soils and associated forest cover in relation to other major soil-vegetation units.

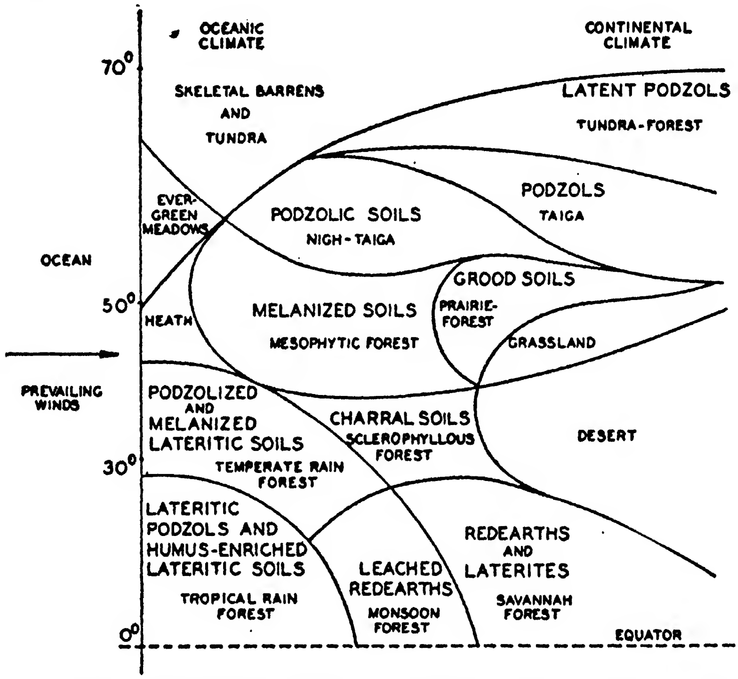


Figure 8. — A schematic outline of the distribution of soils and vegetation based on Brockmann-Jerosch's idea of hypothetic continent.

(1) *Redearths:* — These soils are prevalent in the tropical and equatorial regions with pronounced periods of drought. Morphologically they approach true laterites, especially in their advanced stage of development.

High temperatures and periodically abundant rainfall promote a rapid decomposition of organic matter. Bases and silica are washed downward during the rainy season. Some of the bases, however, are returned to the surface layers by water ascending in periods of drought, and some bases are constantly brought into soluble form by weathering. As a result, the reaction of the soil remains alkaline or slightly acid as long as there is a sufficient supply of base-containing minerals to balance the losses by leaching. Because of the absence of humus and slight acidity, the oxides of iron, aluminum, and phosphorus remain immobile and their relative content steadily increases.

Redearths are characterized by a uniform bright red color and a pro-

nounced granular structure; they often contain iron concretions, referred to as "pseudosand", "iron pea ore" (VAGELER, 1933), and "perdigon" (BENNETT and ALLISON, 1928). At a greater depth, the soil becomes mottled and grades into a zone of decomposition, the so-called "Zersatz" (HARRASSOWITZ, 1926).

Redearth is the predominant type of savannah forest, *i.e.*, extensive areas of grass and scattered umbrella-shaped or round-topped trees; this formation resembles somewhat the "oak openings" of the temperate region. *Adansonia digitata,* the gigantic baobab, *Kigelia aethiopica,* and *Dalbergia melanoxylon* are a few representative tree species of the African savannah forest; *Copernicia tectorum, Cocos coronata,* and *Andira inermis* exemplify the same type in South America. Arborescent *Euphorbias* and species of *Acacia,* occurring on both continents, form a floristic link that connects the African and the South American savannah forests. *Ceiba pentandra* is another cosmopolitan occurring on savannah soils of Africa, Asia, and America. In spite of periodic droughts, some trees on the younger, less ferrallized redearths attain fair dimensions. This is especially true in the regions where savannah occurs at the edge of the tropics or grades into monsoon forest. The savannah forest of Australia, for example, includes species of *Eucalyptus* noted for their size and rate of growth.

In the drier portions, savannah is replaced by the thorn forest, the most xeromorphic and picturesque type of forest vegetation consisting of spiny Acacias, Euphorbias, and Cacti. The replacement may be caused either by a decrease in precipitation or by the occurrence of droughty sandy soils. Both the savannah and the thorn forests occupy a considerable portion of the globe, but have a minor silvicultural importance.

(2) *Indurated redearths:* — In French literature, the aged or *indurated* redearths were referred to as "cuirasse ferrugineuse" or "conglomerats ferrugineaux (CHAUTARD, 1905; LACROIX, 1913). At this extreme stage of development, the redearth is synonymous with the "true laterite"; it is a rock rather than a soil, and moreover, "a rock which cannot be changed back again into the soil by any conceivable process once a certain stage of maturity has been reached." (VAGELER, 1933).

When most of silicate minerals in a redearth become decomposed and the content of bases drops to less than 50 per cent of the exchange capacity, the development of the profile takes a new course. The decrease in acidity below *p*H 5.5 brings a certain amount of sesquioxides into suspension. In the dry season they are brought to the surface in small amounts by the upward movement of water and are irreversibly coagulated (AGAFONOFF, 1930). The iron compounds are converted by oxidation into limonite, and the surface of the redearth becomes covered with "ironstone" or a continuous cindery crust; in time the crust attains a considerable depth and wide extent. Below the iron crust, aluminum hydroxide and hydrargillite accumulate, marking the boundary of the lower zone impoverished in sesquioxides. As VAGELER stated: "The illuvial horizon is thus caused to lie above the eluvial horizon". The accumulation of iron and aluminum oxides on the surface, however, is effected by the upward movement of soil water; the mechanics of this process related to gleization, have been explained in detail by WISSOTZKY (1927).

Indurated redearths are absolutely unproductive from both agricultural and silvicultural viewpoints; their occurrence is largely confined to the savannah region and is marked by areas devoid of any form of plant life.

(3) *Leached redearths:* — In the region of the periodically-defoliated

monsoon forest, with a more abundant rainfall and denser forest stands, redearths are somewhat enriched in humus. On neutral or negative topography they exhibit a downward translocation of sesquioxides resembling podzolization. The reduction of iron and the development of a light-colored surface horizon in such *leached redearths,* however, is largely due to "surface gleization", *i.e.,* a rain-soaked condition prevalent during the wet season. According to HARRASSOWITZ (1930), large areas of the dry regions of the tropics are covered with a sheet of water during the period of rains. These peculiar conditions of soil development are termed by MOHR (1944) "amphibious weathering". The layer of forest litter, which is accumulated during the dry season, is likely to contribute to the processes of reduction and solution of resistant compounds.

In spite of a low base exchange capacity and a low content of readily-available nutrients, as determined by the generally accepted methods of soil analysis, leached redearths support highly productive and valuable stands of monsoon forest. The nutritional requirements of trees on these soils are satisfied chiefly through biological fixation of nitrogen and a constant release of nutrient elements from the weathering minerals. Some available nutrients may be held in the form of anionic exchange (MATTSON, 1931), and some may not be available without participation of mycorrhizae. Mycotrophy, epiphytism, and activity of legumes are of unparalleled importance in the nutrition of tropical forest vegetation. Because of these conditions, a special technique of analysis will have to be worked out for the indirect evaluation of fertility in tropical forest soils.

Although monsoon forests occur throughout the tropics, their silviculturally important portion at present is confined largely to India, Burma, Indo-China and the East Indies. The stands of this region are of great interest to a forester, especially because they include one of the world's most valuable species, teak, *Tectona grandis.* This is one tree of the tropical forest that has long been cultivated in plantations, particularly in Java and India. Among the many other members of the monsoon forest the following are outstanding: *Acacia leucophloea, Albizzia procera, Sterculia villosa, S. virens, Grewia elastica, Duabanga grandiflora, Erythrina suberosa,* and species of bamboo. Because of periodic droughts, the ground cover of the monsoon forest is scant and lianas are few in number; therefore, the interior of the forest is readily accessible and silviculture can be practiced much more easily than in the rain forest. Some of the redearths under monsoon forest, notably those derived from ferro-magnesian rocks, are among the most productive agricultural soils of the tropics. The position of the monsoon soil-forest type in relation to rain forest and savannah is instructively presented by HARRASSOWITZ (1930), whose scheme is reproduced in Figure 9.

(4) *Charral soils:* — For lack of an available term, the name of these soils was derived by the writer from the word "charral" or "charralon", used in Latin America as a synonym for sclerophyllous forest. This park-like evergreen forest consists of oaks, laurels, olive-trees, and other hard-leaved trees and shrubs often growing in association with megathermic pines, junipers, and cypresses (SCHIMPER, 1903; DENGLER, 1930). The sclerophyllous forest is a distinctive formation that partakes in nearly equal degrees of the characteristics of a forest, a heath, and a desert. The name "charral soils", consequently, is used in this book as a broad zonal term

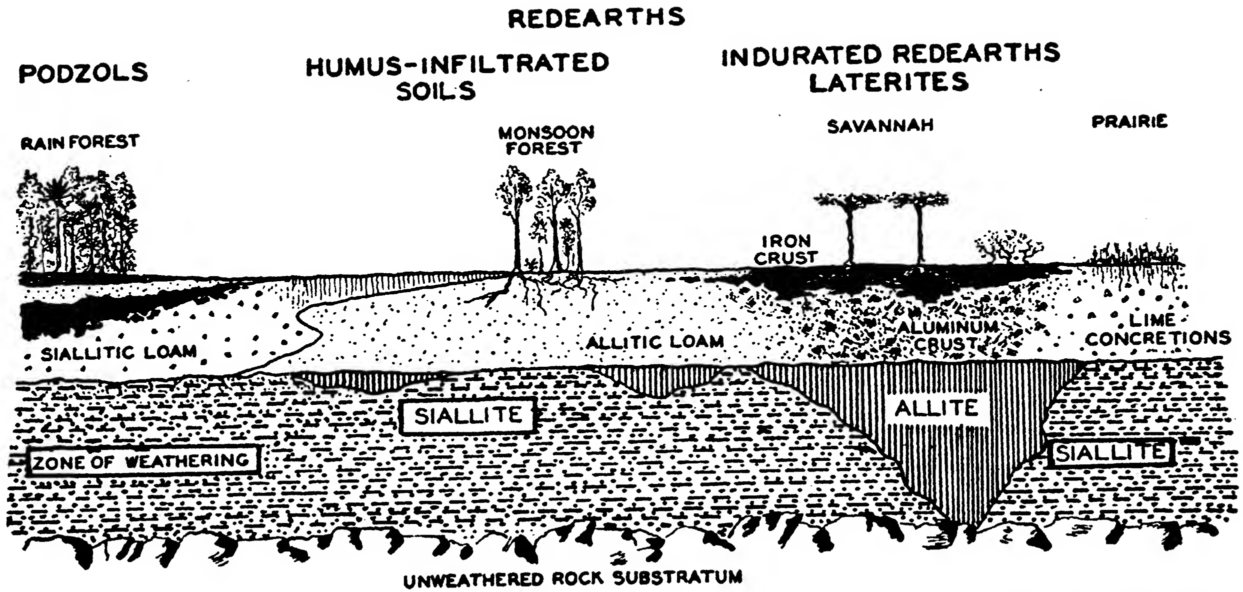


FIGURE 9.—A schematic outline of the distribution of most important types of tropical soils. (*Adapted from* HARRASSOWITZ).

analogous to "tundra soils" or "prairie soils". There is only fragmentary information on soils supporting sclerophyl forest and the question of their genesis can not be definitely settled without further studies.

Sclerophyllous forest is found predominantly in the littoral districts of the sub-tropics, but never in the tropics proper. The most important areas are on the European and African coasts of the Mediterranean Sea, in South Africa, central Chili, California, and southern Australia. These regions are characterized by sharp contrasts in climatic conditions, *i.e.*, mild rainy winters and hot summers with prolonged periods of drought. Although the total annual precipitation approaches the rather high level of 30 inches, the dry summer seasons impart a pronounced xerophytic stamp to the floristic cover and desert-like features to the soils. Organic remains undergo a rapid and usually a complete mineralization; the humus horizons in charral soils are of a "lean mull" type and are similar to those of savannah soils. High temperatures throughout the year and periodic rainfall lead to partial desilication, and a consequent enrichment of soil material in aluminum and iron oxides. As a result, soils usually have red or reddish-brown colors and a high percentage of fine soil material. During the rainy winter season, some soluble salts and colloidal material are moved downward. The colloids are deposited irreversibly and contribute to the development of the accumulative horizon, which in mature soils shows an increased content of clay particles, an intense color, and often a coarse prismatic structure. The differentiation of horizons is more pronounced in charral soils derived from non-calcareous parent materials. Some of the soluble salts, translocated in winter, are returned to the surface stratum by the activity of plants and summer evaporation. Therefore, the entire body of the soil retains its supply of bases and a slightly alkaline to slightly acid reaction. Acid soils occur as an exception on siliceous substrata supporting pines.

In the light of present limited knowledge, charral soils may be considered as close relatives of savannah soils; however, laterization occurs in charral soils only in a mild form and is partially offset by soil-forming processes of a semi-desert type. The soils supporting sclerophyllous forest in the California region were originally related by THORP (1936) to the brown soils of Shantung province in China. More recently they were designated by an ambiguous term, "non-calcic brown soils" (BALDWIN *et al.*, 1938). These soils actually have an abundant supply of calcium and support predominantly calciphilous trees, including both deciduous and coniferous species.

One of the many petrographic varieties of soils found under scleraphyllous forest, namely "terra rossa", has received considerable attention from soil scientists (GALDIERI, 1913; LEININGEN, 1917; REIFENBERG, 1929; BLANCK, 1930). This type is prevalent on the shores of the Mediterranean Sea where it is confined to calcareous substrata, particularly hard limestones and marbles. A deficiency of litter, a weakly developed horizon with incorporated humus, and a brightly colored fine-textured red substratum are the outstanding morphological characteristics of these soils. In places the soils contain iron-coated fragments of lime. The unweathered limestone occurs at a depth varying from a few inches to several feet. From a generical standpoint, terra rossas and rendzinas occupy a somewhat similar position. It is possible that some terra rossas represent an advanced stage in the development of rendzinas within the region subject to laterization. A substratum of soft limestone, however, is said to be essential for the development of dark-colored humus-calcareous soils (GLINKA, 1931).

Terra rossa and other varieties of charral soils, such as the iron-rich "ferretto" and siliceous "macchie" soils of Europe, the "fynbush" soils of South Africa, and the ferruginous sands of Australia, have only a subordinate silvicultural importance; the sclerophyllous forest exhibits within its entire region the same general floristic appearance and low rate of growth.

In the moister portions of the charral region there occur intrusions of melanized soils which support forest types of radically different composition and rate of growth. Mixed stands of chestnut, walnut, ash, and poplars in the Mediterranean region may be given as an example of such as intrusion; the redwood stands of California with a ground cover of sclerophyllous plants present another case of this kind.

The following typical representatives of the sclerophyllous, or "leather-leaf" forests of Europe and northern America should suffice to illustrate the floristic physiognomy of charral soils:

Europe: *Quercus suber, Q. ilex, Q. lusitanica, Laurus nobilis, Buxus sempervirens, Arbutus unedo, Oleo europea, Pistacia lentis, Cupressus fastigiata, Pinus pinea, P. maritima, P. aleppensis, P. canariensis.*

North America: *Quercus wislizeni, Q. gambelii, Q. dumosa, Umbellularia californica, Castanopis chrysophylla, Prunus ilicifolia, Ceanothus spp., Arctostaphylos glauca, Cupressus macrocarpa, Pinus edulis,* and *P. monophylla.*

Because of the low density and depressed rate of tree growth, the leather-leaf forest is of little interest to a silviculturist concerned with timber production. Nevertheless, this association fulfills several highly useful functions; it provides fuel, prevents erosion, and affords some shade from the hot sun. Paradoxically enough, some of the charral soils produce returns, under planned management, incomparably greater than do most other groups of forest soils. These soils are well adapted to the production of citrus trees, particularly oranges, and other valuable horticultural plants of sclerophyllous nature. From the broad viewpoint of tree culture, therefore, the charral soils deserve much greater attention than they have received in the past.

(5) *Humus-infiltrated lateritic soils:* — The enrichment of soil in humus occurs widely throughout the tropical and sub-tropical regions, especially in rain forests. The rain forest with its several stories of trees and shrubs and a continuous leaf-fall produces forest litter at an annual rate exceeding one hundred tons per acre, air-dry weight. A fraction of this enormous quantity of organic matter escapes complete decomposition on the surface and is infiltrated into the soil as a colloidal suspension. As analyses show, the surface layers of many tropical soils have as much as 6 per cent of organic matter (BENNETT and ALLISON, 1928). Some virgin soils of Tanganyika in Africa were reported to contain as much as 11 per cent of incorporated organic matter (ROBINSON, 1932). A still higher content of humus was found by DEAN (personal communication) in some forest soils of the Hawaiian Islands. According to VAGELER, "contents of humus running up to 10 per cent for the topmost layers are no rarity". The same writer indicated that the depth of humus infiltration in some tropical soils reaches several yards.

In spite of the high content of infiltrated humus, many soils of the tropical region do not reveal its presence; instead the fresh cuts of such soils exhibit a thin layer of undecomposed litter underlain by a bright red or yellow mineral soil. The absence of dark tints is due to the fact that the colloidal humus of the tropics often is either colorless or only faintly colored. Dark colors develop in the soil, however, after a period of exposure of the soil cut to the air. To some extent, a coating of ferric iron is also responsible for masking the organic matter.

Light colored soils containing humus are confined chiefly to the regions of tropical rain forest; humus-enriched soils with a pronounced dark or brown horizon occur predominantly in the sub-tropical regions. These two broad groups of humus-infiltrated soils of the lateritic zone may be designed as *concealed humus soils* and *melanized lateritic soils,* respectively.

The colorless humates are known to possess a high degree of acidity and a very low carbon-nitrogen ratio; they retard allitization and thus favor indirectly the development of siallitic soils. Many properties of soils with concealed humus horizons still await investigation. More information has been accumulated on soils with pronounced humus layers. A comprehensive description of such soils from the forests of Hawaii (yellowish-brown and reddish-brown lateritic soils), is given in the U. S. D. A. Yearbook (1938, p. 1154). Total analyses reported by BENNETT and ALLISON (1928) for the "mulatto" or "tierra negro-clara" and related soils of Cuba are of particular interest in regard to the profile composition of tropical soils enriched in humus.

The petrographic origin of all humus-infiltrated soils and especially their content of basic minerals exert a profound influence upon their morphology and productivity. Soils formed on parent materials low in bases are usually structureless and greasy like soap; they are characterized by a high percentage of silica, a yellowish color, strong acidity, and a general tendency to become podzolized. In contrast, soils derived from basic substrata contain base-saturated humus and have a slightly acid reaction, seldom below *p*H 6.0; they exhibit excellent crumb structure, and are, according to VAGELER, "the dream of the agricultural pioneer" (1933, p. 87).

The humus-infiltrated soils support a multitude of tree species. In some instances as many as 60 to 80 tree species can be identified on a single acre (BÜSGEN, 1910). The predominant association on these soils, the tropical rain forest, is a most highly organized community of plants and animals. This biocenotic unit does not tolerate a vacuum and utilizes the productive forces of environment not only by the canopy of the main stand, but also by several understories of trees and shrubs, numerous epiphytes and lianas. At the same time, the tropical rain forest has an uncertain silvicultural or utilitarian value. The number of merchantable trees, such as mahogany, often does not exceed one or two per acre. Logging encounters great difficulties because of the density of stands and high percentage of worthless material. The conditions are somewhat better near the limits of the tropical rain forest region where lianas and undergrowth are less abundant. The value of the tropical rain forest frequently rests not so much in its wood, but in certain forest by-products such as oil, rubber, drugs and fruits.

In a planned agricultural utilization of tropical regions, humus-infiltrated soils play a part of unique importance. These are the principal soils in the tropics that preserve a reasonable degree of fertility after clear cutting and especially under cultivation. Indiscriminate cultivation, however, rapidly ruins even the so-called "inexhaustibly rich tropical soils". With the exception of annual cotton and sugar, most tropical crops are perennial mycorrhizal plants, *i.e.,* trees and shrubs; many of them, such as cinchona, coffee, tea, and rubber, are dependent on the supply of humus.

(6) *Lateritic podzols:* — Whenever tropical or sub-tropical rain forest invades an area of laterized soils, it tends to initiate podzolization. Strongly laterized substrata deficient in bases are especially subject to translocation

of sesquioxides. Impeded run-off or the proximity of ground water are further conditions promoting deferrallization, *i.e.*, the development of podzolized soils.

The podzolization of tropical soils becomes pronounced as soon as their reaction drops below *p*H 5.5 (VAGELER, 1933); it follows essentially the same course as podzolization in the temperate zone, and gives rise either to strongly podzolized raw humus soils, *i.e.*, *lateritic podzols*, or moderately podzolized soils, covered with a comparatively thin and friable layer of organic remains, *i.e.*, *podzolized lateritic soils*. A high content of bases, such as is often found in slightly laterized "young redearths", and a rapid decomposition of forest litter, may keep the sesquioxides in a state of immobility. In such cases, the soil profile may retain for a long time the features of a humus-infiltrated soil, *i.e.*, a soil equivalent to the *weakly podzolized soils* of temperate regions.

The accumulation of acid raw humus and the development of true podzols usually take place in tropical regions where annual rainfall approaches 300 inches (LANG, 1915). Such soils are particularly common on areas having a ground water table at a fairly shallow depth (VAGELER, 1933). According to the few descriptions thus far reported, there is but slight difference between the composition of tropical podzols and podzols or gley podzols of the temperate zone. A yellowish leached layer, sometimes exceeding 30 inches in depth, may be mentioned as a special characteristic of podzols in the tropics. The ortstein horizon is met only in permeable sandy or sandy loam soils, whereas heavy soils develop an impervious mottled B horizon. The lateritic parent material, or its upper portion, is usually deferrallized and has a rather high silica-sesquioxide ratio; accordingly, it is rated as siallitic (HARRASSOWITZ, 1930).

The value of podzol soils as a medium for plant production decreases in direct proportion with the increase in leaching and acidity. Soils with a deep leached horizon are particularly poor in nutrients and undesirable for agricultural use. Hardpan layers present a serious obstacle to the cultivation of deep-rooted plants, such as rubber, *Hevea brasiliensis*. Intensive cultivation of podzols has the same adverse effect on soil fertility in the tropics as it has in temperate regions. Podzols and related raw humus soils of the tropics have been, until recently, entirely overlooked by investigators; in fact, many statements may be found in the older literature denying the possibility of any appreciable accumulation of organic remains in tropical or subtropical soils.

(7) *Podzolized lateritic soils:* — Moderately leached soils of lateritic substrata are largely confined to the region of sub-tropical and temperate rain forests. Such soils lack the layer of true raw humus and their horizon with incorporated humus is only slightly developed or entirely absent. The leached layer consists of a reddish-grey or yellowish-grey quartzose residue. It is underlain by an intensely colored lateritic substratum of heavy texture. The analyses of upland soils show, as a rule, that the colloids are not concentrated in a distinct accumulative horizon; instead their content progressively increases to a depth of several feet (MARBUT, 1935). The diffusion of leached colloids seems to be the peculiar morphological feature of the podzolized lateritic soils. It is reasonable to suppose that flocculation of the colloidal suspensions is hindered by the deficiency of dispersed humates

as well as by the low content of mineral exchange material and electrolytes in the entire lateritic substratum.

The morphology of a podzolized lateritic soil is exemplified by the following description of a profile developed under a stand of longleaf pine in southern Mississippi:

A_0 A layer of loose pine needles.
A_1 1". Dark layer of sandy loam with some incorporated humus and charcoal.
A_2 1-9". Reddish-grey leached sandy loam of a strongly acid reaction.
B 9-30". Intensely red to reddish brown clay of faint coarse lump structure, somewhat compacted and sticky, with dark brown veins and flakes; acid reaction.
C Structureless sticky and mottled clay.

Two more or less distinct morphological varieties of podzolized lateritic soils are recognized by soil scientists: red soils and yellow soils. The color of yellow soils has been attributed to their youth, incipient podzolization, or previously impeded drainage (STREMME, 1915; MARBUT, 1935). According to the writer's observations, the difference in color does not play an important part in the distribution and growth of forest vegetation.

In the opinion of some pedologists, the podzolized lateritic soils of the southeastern United States, France, the Caucasian region, and Japan (STEBUTT, 1930) were formed on fossil laterities which survived from the Tertiary Period (GLINKA, 1931). In that period, according to WEGENER, (KOEPPEN-WEGENER, 1924), the equator passed through southern Spain, the vicinity of the Caspian Sea and northern India. Recently, the ideas of WEGENER were used by WULFF (1943) in his work on the distribution of plants throughout the world.

Podzolized lateritic soils are strongly acid, deficient in base exchange material, and have a low content of nutrients. In many instances, the deficiency of nutrients in all of the textural classes, including the clays, makes these soils suitable only to pine species and other less exacting trees (PESSIN, 1933; TURNER, 1938). The podzolized lateritic soils of the southeastern United States support predominantly *Pinus palustris, P. taeda, P. caribea,* and *P. echinata;* these grow alone or in association with light-demanding oaks, such as *Quercus velutina, Q. stellata,* and *Q. prinus.* Among other trees common in the region of podzolized lateritic soils of America, the following should be mentioned: *Magnolia accuminata, Nyssa silvatica, Liquidambar styraciflua, Quercus virginiana, Fagus caroliniana,* species of *Carya* and *Juniperus.* Most of these trees, however, occur on melanized and alluvial soils interspersed with podzolized lateritic soils.

The forest cover of the podzolized lateritic soils of far-eastern Asia may be used to illustrate the parallelism in the distribution of soils and forest vegetation; some of its outstanding species are: *Pinus luchuensis, P. thunbergii, Torreya, Cryptomeria japonica, Juniperus rigida, Quercus serrata, Q. glandulifera, Magnolia precia, M. denudata,* and *Phellodendron japonicum.*

On podzolized lateritic soils, the less exacting species, particularly pines, attain a fairly high productivity because of their moderate nutrient requirements and the long growing season. Accessibility of stands throughout the year, favorable conditions for both natural and artificial reforestation, and the rapid early growth of trees are among other silviculturally important features of forests on these soils. Many tracts of these soils, located in the

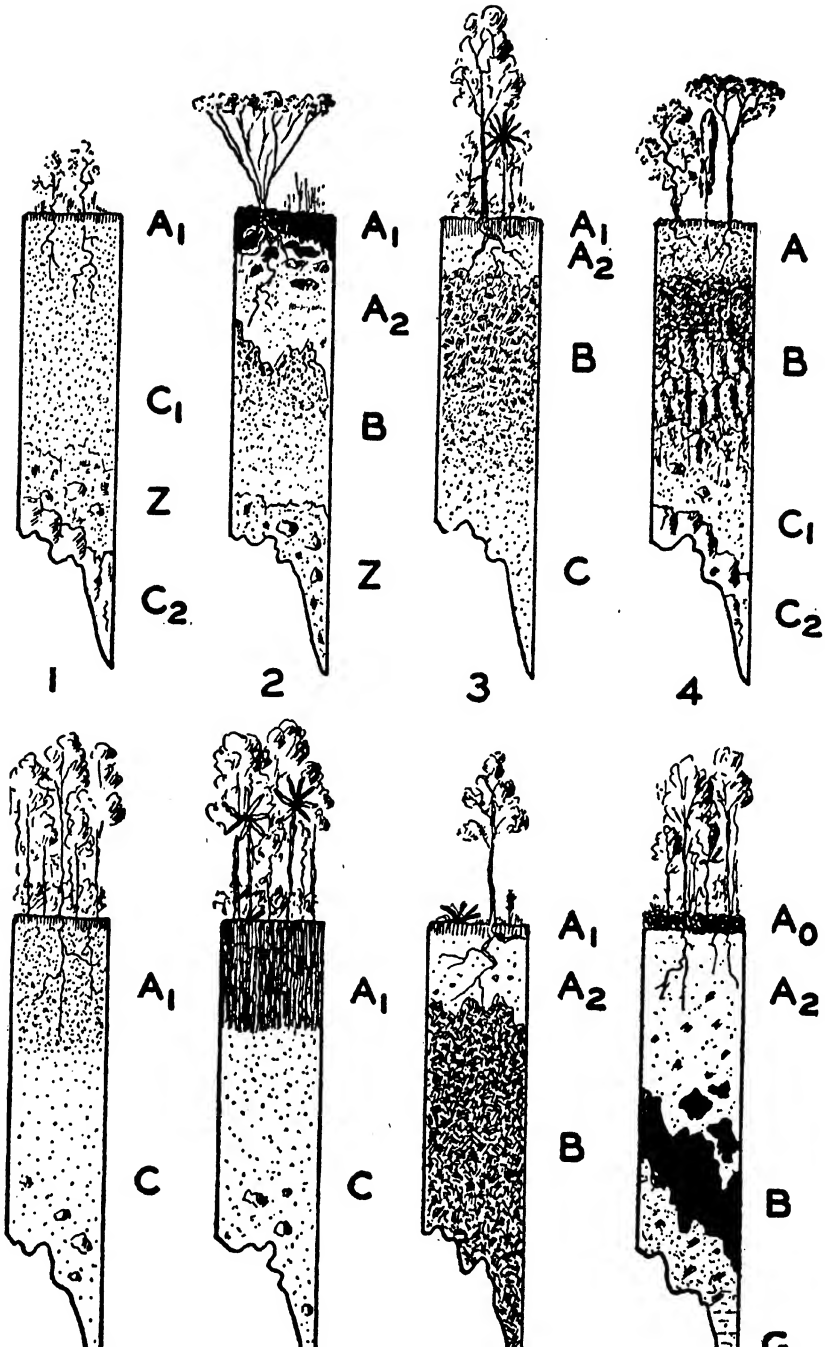


FIGURE 10.—Representative profiles of important forest soils of the lateritic type of development: 1. Immature redearth; 2. Indurated redearth or laterite; 3. Leached redearth; 4. Charral soil; 5. Concealed humus soil; 6. Melanized lateritic soil; 7. Podzolized lateritic soil; 8. Lateritic podzol.

United States, have been artificially reforested and placed under silvicultural management. Utilization for agriculture is limited largely to the growing of cotton, peanuts, sweet potatoes, and some sub-tropical crops.

Figure 10 illustrates schematically the morphology of important genetic types of lateritic forest soils.

Mountain Forest Soils: — The study of mountain soils by DOKUCHAEV (1899) revealed that the soil regions, or zones, succeed each other in a definite order as the altitude increases from sea level. This altitudinal or vertical zonality of mountain soils is analogous to the latitudinal or horizontal zonality found on the plains. The correlation between the vertical and horizontal zonalities of soil groups is especially pronounced in European Russia. The Great Russian Plain extends from the Arctic Circle to the Caucasian Mountains. The territory from north to south and from sea level to its highest altitude includes a wide range of climates and soil conditions (ZAKHAROV, 1931). The attached diagram illustrates schematically the relationship involved (Fig. 11). The Rocky Mountains (THORP, 1931; PEARSON, 1931), as well as the other mountain ranges of the United States, present similar examples of the vertical zonality of soils.

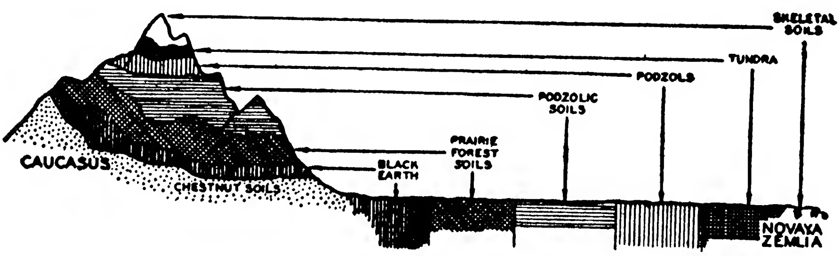


FIGURE 11. — Relation between the horizontal and vertical zonality of soils in European Russia. (*Adapted from* ZAKHAROV).

An instructive example of vertical zonality of forest soils in the Central Alps (Northern Italy) is given by JENNY (1930); it is reproduced here in an abbreviated schematic form:

ALTITUDE:	SOIL GROUP:
100- 200 m.	*Yellow and red earth,* largely iron-enriched soils of moraines.
200- 700 m.	*Brown earths,* more or less depleted in bases, and *Rendzinas* on calcareous substrata of higher elevations.
700-1,700 m.	*Podzol soils* including both strongly and weakly podzolized varieties.
1,700-2,700 m.	*Alpine humus soils,* sometimes only a few inches deep.
2,700-3,500 m.	*Skeletal soils* grading into a zone of ice and snow.

The distribution of different zonal types in the mountains is, of course, greatly affected by the geographical location, exposure, gradient, and composition of the parent rock, and the zonality of the soils is of an irregular character (SMIRNOFF, 1914). The differentiation of horizons and the development of genetic soil types are less pronounced in the mountains than on the plains because of continuous erosion and deluviation. The deep and more fertile soils of deluvium are often intersected by the shallow and less productive residual soils of denuded areas, or by rock outcrops. The presence of rock fragments of various sizes is characteristic.

The mountain soils of the foothills do not differ radically from the soils of the plains. Depending upon the geographic location of the mountain range, they may be either desert, grassland, or forest soils of various large groups (GLINKA, 1931). With an increase in elevation, the foothill soils of high mountains grade into mountain podzols, sod soils, peat bogs, mountain tundra, and skeletal soils. Mountain podzols and sod soils are not quite comparable to the forest soils of the plains and are described below.

(1) *Mountain podzols:* — The cool and humid mountain belt of these soils is characterized by the prevalence of physical weathering, with little formation of fine soil material. These soils have less distinct horizons than the podzols of the plains, and seldom have cementation of the illuvial layer or iron concretions. Nevertheless, the analysis of mountain podzols reveals a pronounced depletion of the upper layer in bases, sesquioxides, and colloids. The humus content is high, reaching in some cases 12 per cent. The exchange material is composed chiefly of humates which are saturated with hydrogen and give the soil an acid reaction (ZAKHAROV, 1931).

The mountain podzols support microthermic species, such as spruce, fir, larch, pine, birch, and mountain ash. These species produce only low yields because of the properties of the soil and the short growing season. At their lower boundary, mountain podzols grade into far more productive podzolic soils. The upper boundary of these soils is formed by sod soils and alpine meadows. Highmoor peat swamps are found throughout the region of mountain podzols.

(2) *Sod soils:* — These soils are found under open forest stands. They are characterized by a weakly developed sod layer, and a grey or brownish-grey top soil which becomes lighter with depth. A chemical analysis of the profile shows a removal of some sesquioxides from the upper layer, although no differentiation into A and B horizons is noticeable in a field examination. On northern exposures the upper layer of sod soils is usually light grey, whereas on southern exposures it is brownish grey. The sod soils penetrate as tongues into mountain meadow soils and sometimes occupy small areas in the region of alpine meadows. In places they develop a deep humus horizon and take on a character of "alpine humus" soils (LEININGEN, 1908). Sod soils contain as much as 40 per cent of coarse gravel. They support mountain varieties of larch, fir, spruce and pine. A list of typical species found on sod soils and mountain podzols, comprising so-called "alpine forest", is as follows:

North America: *Tsuga mertensiana, Abies lasiocarpa, Picea engelmannii, Pinus albicaulis, P. flexilis, P. aristata, Larix layalli,* species of *Betula, Salix,* and *Sorbus.*

Europe: *Picea excelsa, Pinus montana,* var. *uncinata* and var. *mughus, P. cembra, Larix europea,* species of *Betula,* especially *B. nana, Sorbus aucuparia.*

Asia: *Abies pindrau, Picea obovata, P. morinda, Larix griffithii,* species of *Betula, Salix* and *Sorbus.*

Figure 12 presents a generalized map of the major forest soil regions of the world. Plate 4 illustrates some characteristic forest covers of the major soil groups.

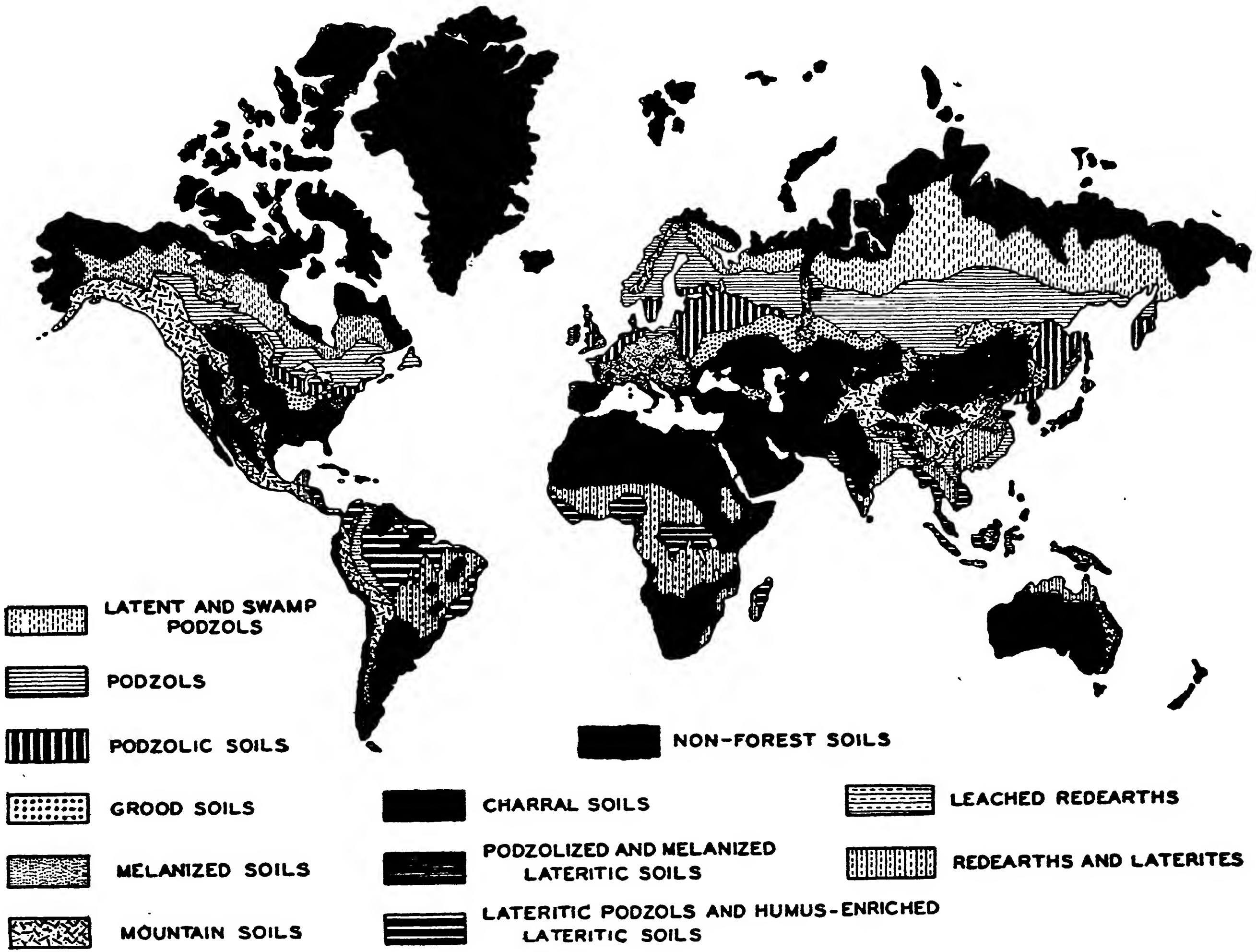


FIGURE 12. — Generalized map of the forest soil regions of the world.

Chapter IV

GENETIC SOIL GROUPS OF THE WORLD; HYDROMORPHIC AND EMBRYONIC SOILS

Gley Soils (Ground Water Soils): — Gley soils develop under the influence of ground water. Anaerobiosis and hydrolysis, dominating the strata of soil below the ground water table, produce deoxidized, often highly dispersed, sticky gley horizons, mottled with reduced oxides of iron (WISSOTZKY, 1905). Soils in which the gley layer occurs within the reach of the main root system of trees or cultivated plants, *i.e.,* at an approximate depth of seven feet or less, are classified as gley soils.

The process of gleization may affect any genetic group of soils. The resulting varieties are referred to as gley podzols, swamp podzols, gley laterites, vlei soils, meadow soils, lowland prairie soils, ferruginous soils of mountain valleys, marl soils, etc. When the organic layer attains a thickness greater than 6 inches, the gley soils are referred to as "organic soils" or "peat" and considered as a special group.

Ordinarily, gley soils occur sporadically, being confined to depressions and areas underlain by impervious substrata. However, in certain regions of America, northern Europe, Siberia, and Africa, gley soils are a dominating type occupying hundreds of thousands of acres.

Although gley soils have numerous varieties, their morphology may be illustrated by the following generalized profile description:

A_0 Dark to black partly decomposed organic remains, often of peat-like nature.
A_1 Nearly black layer with infiltrated humus.
A_2 Light colored, podzolic or podzol-like leached layer, sometimes with mottling by ferrous iron and other reduced compounds.
B Brown or greyish-brown accumulative horizon enriched in sesquioxides; often not present.
G_1 Mottled, bluish-grey, rusty, bluish-brown, ochreous, or humus-ochreous gley.
G_2 Greenish or bluish, wet or moist, deoxidized gley layer, impoverished in iron and somewhat enriched in colloidal silica.

The reaction of forest gley soils is usually acid in the upper part of the profile, but may be neutral or alkaline in the zone of water saturation. The high content of bases appears to be an outstanding characteristic of gley horizons (ALBRECHT, 1941).

In detailed genetic studies, the variations in the degree of soil drainage, or in the intensity of gleization are described by a number of terms such as gley podzol, swamp podzol, podzolic gley soil, podzolic gley soil with a deep gley layer, peat podzol, gley podzolic peat soil, peaty gley soil and swamp gley soil (ZAVALISHIN and PRONEVICH, 1928). These and similar terms have significance in the morphological nomenclature of soil genesis, but they are too long and confusing for practical soil classifications. Moreover, they have no direct bearing upon the productivity of soils, particularly forest soils.

The composition of the forest stand, its rate of growth, percentage of cull material, vigor of competing vegetation, possibilities of natural reproduction, stability of the forest against the wind, and other silviculturally

important features are chiefly influenced by the *distance* of the gley layer from the surface (KRUEDENER, 1927). This determines the accessibility of water, the extent of root penetration and the depth of well-aerated soil containing available nutrients. Considering the depth and position of the gley layer in relation to the occurrence of the A, B, and C horizons of a mature forest soil profile, the following three types of gley soils may be recognized (WILDE, 1940*b*):

Alpha-gley soils or *shallow gley soils,* that is semi-swamp, more or less permanently wet soils with a shallow gley layer grading into A_2 or A_1 horizon.

Beta-gley soils or *mid gley soils, i.e.,* insufficiently drained, periodically wet soils with gley layer superimposed upon the B horizon.

Gamma-gley soils or *deep gley soils, i.e.,* sufficiently drained, but rather moist soils with a deep gley layer occurring in the C horizon.

(1) *Alpha gley soils* (*Shallow gley soils*): — The gley layer extends through the leached horizon, and may reach the horizon with incorporated humus, being thus within about 1 foot of the surface. In this type the influence of the ground water often masks all the other genetical features of the soil profile. Alluvial stream bottom soils, soils of semi-swamp flats of lacustrine clays or highly colloidal weathered drifts of early glaciations, and various swamp-border soils belong to this group.

The forest cover of alpha-gley soils is composed of a rather limited number of species which can tolerate deficiency of aeration. Spruce, balsam fir, cedars, bald cypress, pitch pine, black ash, elm, some oaks, cottonwood, and tupelo gum may be cited as typical representatives. With some exceptions, the stands are of a low productivity and have a high percentage of cull material (ZAVALISHIN, 1928; BÜSGEN and MÜNCH, 1929; TAMM, 1931).

(2) *Beta-gley soils* (*Mid gley soils*): — The gley horizon occurs immediately below the accumulative layer and sometimes grades into the latter, thus being at a depth of 2 to 3 feet from the surface. Percolating water and ground water contribute equally to the morphology of these soils. The soils of lower slopes in the mountains, shallow outwash or residual soils underlain by impervious strata of weathered shale or boulder clay, borders of lowland prairie soils in the transitional prairie-forest region, some red and yellow lateritic soils underlain by hardpan, and podzols of heavy texture with highly colloidal accumulative layers are typical examples of beta-gley soils.

In the summer, the surface layers of these soils are usually dry. In the fall, and particularly in the spring, however, water saturates the entire surface layer. An examination of open trenches, or deep auger borings are necessary to reveal the presence of the typical "mottling" of the gley horizon and the true nature of these soils.

Being a transition, this type of soil offers a suitable site for the survival of both upland and lowland forest trees, even if it does not assure their successful growth. Consequently, the forest cover is composed of numerous species, both conifers and hardwoods. The productivity and the stability of forest lands on beta-gley soil are lowered by a number of adverse conditions. The roots of the trees are confined to a comparatively shallow surface layer of well aerated soil. As a result, the supply of available

nutrients is limited. Periodic saturation and the effect of early and late frosts greatly shorten the length of growing season. Upland species suffer in spring and fall from deficiency of aeration, whereas lowland species suffer and sometimes perish in summer from drouth. The abundance of weakened specimens encourages the development of parasitic organisms which contribute to the general decadence of forest stands.

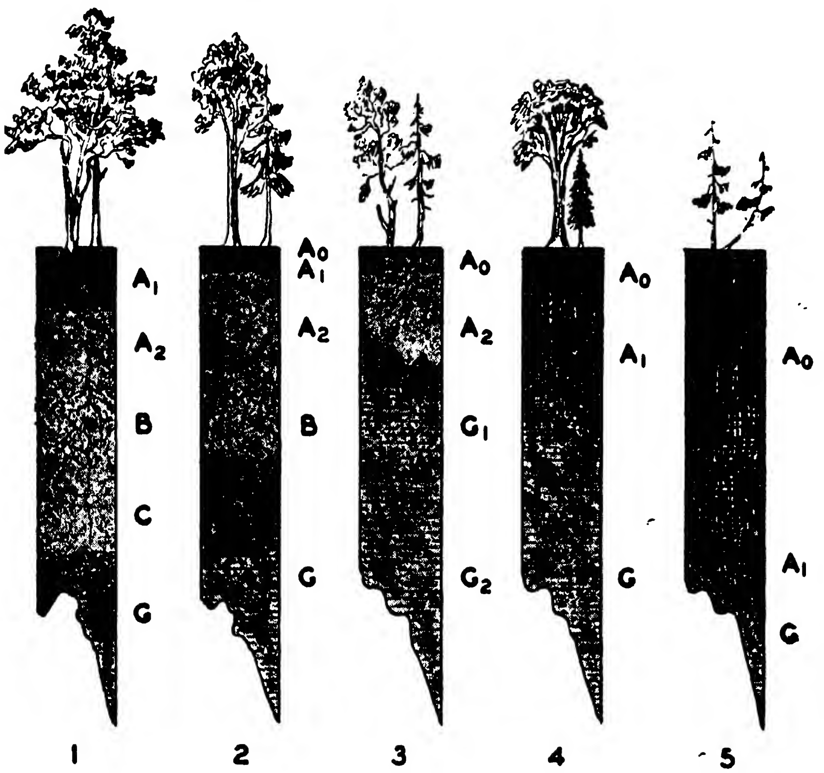


FIGURE 13. — Representative profiles of soils formed under influence of ground water. 1. Weakly podzolized loam with a deep gley horizon or gamma-gley loam; 2. Podzolic loam with a gley horizon reaching the accumulative layer or beta-gley loam; 3. Podzolic loam with a shallow gley horizon or alpha-gley loam; 4. Muck or stream-bottom soil high in organic matter and with a shallow gley horizon; 5. Peat or organic soil.

(3) *Gamma-gley soils* (*Deep gley soils*): — The gley horizon reaches its full development in the lower part of the parent material, usually at a depth of from 5 to 7 feet. However, slight mottling may occur at a depth of about 4 feet. The development of mull humus is often characteristic of gamma-gley soils. In all other respects, the composition of the soil profile is but slightly influenced by the ground water.

The roots of the trees develop in a sufficiently deep, well-aerated, and potentially fertile layer of soil, and receive some additional moisture from the ground water. Of great importance is the relatively stable ground water table, protected from evaporation by a substantial mantle of soil. Such favorable conditions usually lead to an exceptionally rapid growth of timber

and to general stability of forest stands. The composition of stands does not differ conspicuously from those growing on true upland soils. However, the presence of a deep gley layer may be responsible for the occurrence of more exacting species than are ordinarily found in a given region on upland soils of similar texture (WILDE, 1929*a*).

Figure 13 includes examples of soil profiles formed under the influence of ground water table.

Organic Soils (Moors): — Organic soils are formed under conditions of excessive moisture resulting from either high humidity or impeded drainage. They are composed of a surface layer of organic remains exceeding 6 inches in thickness, and a water-logged gley substratum. The organic soils developed on uplands of highly humid, cold regions are called *high moors* or *raised bog soils*. The organic soils formed in depressions are called *low moors* or *swamp soils*.

(1) *High moor soils:* — In the cold and humid belts of high mountains or in coastal regions the activity of microorganisms is slowed down to such an extent that the development of peat deposits takes place not only in depressions but on upland areas as well. In such localities, remains of plants, chiefly mosses, accumulate to a height of several feet and rise above the neighboring ground as extensive mounds. Because high moors are not dependent upon the occurrence of ground water, but receive their moisture from precipitation, they are also called "atmospheric swamps". The development of this peculiar type of organic deposits proceeds not only on level areas, but also on gentle slopes.

In many instances, high moors originate under forest cover and their genesis is related to the process of podzolization. The depletion of the surface layer of a forest soil in bases promotes the accumulation of raw humus which increases the water-holding capacity of soil and encourages the invasion of mosses, especially *Sphagnum*. In time, mosses cover the area as a solid blanket. The insulating effect of *Sphagnum* produces a considerable difference in the summer temperature of soil and atmosphere, hindering the normal transpiration of trees (TANFILIEV, 1903). Simultaneously, the aeration of soil falls below the level satisfactory for the growth of most forest trees. Forest stands gradually degenerate and give way to heath shrubs and other high moor vegetation.

The profile of high moor peat is the simplest of all organic soils; it consists predominantly of slightly altered remains of *Sphagnum*, compressed at a greater depth into a light yellowish-brown mat. The layer of mosses rests either on weathered rock or on a transitional layer of partly decomposed reeds and sedges.

High moor peat is very strongly acid, with a reaction often as low as *p*H 3.0; it is very low in nitrogen and mineral nutrients, but often has a high base exchange capacity. The sporadic cover of struggling forest trees is composed of a few species, such as Scotch pine, several mountain pines, black spruce, and dwarf birch. The entire association of high moor shows pronounced signs of xeromorphy. The excavated peat material is used for surgical purposes, as absorbent farmyard litter, for improvement of physical properties of soils, their acidification, and as a carrier of commercial fertilizers.

(2) *Low moor soils:* — Low moor soils are formed throughout the forest region by accumulation of plant remains in shallow lakes, ponds, and

abandoned stream meanders. The process of development is usually initiated by reeds, sedges, and similar shore-line plants which gradually creep toward the center of the basin as their remains accumulate and offer them a suitable foothold. The accumulation of debris is assisted by algae and mosses which float on the surface as consolidated layers or mats. Such mats of mosses and other water-loving vegetation may cover the lake completely and convert it into a "quaking bog" or "quagmire". The floating mat may attain a considerable thickness, become water-logged and sink to the bottom of the lake as an inter-layer of the eventual peat deposit. If conditions permit, shrubs and trees invade the shore deposits and floating mats, and contribute to the development of peat. Thus, depending upon the nature of plant remains, the swamp deposits may consist of several more or less distinct layers.

In the advanced stages of development, the conditions of drainage and the nature of the mineral substratum determine the type of vegetation that occupies the low moor deposit and imparts to its surface layer certain morphological features. According to the predominant kind of plant remains, the low moor soils are designated as *sedge peat, woody peat, moss peat, sedge-moss peat,* and so forth. Sometimes the classification is more specific, and types such as *Sphagnum peat, Hypnum-sedge peat, Papyrus peat,* and *cedar-fir peat* are recognized. Furthermore, low moor soils are classified according to degree of decomposition of organic matter into "fine textured" or "well decomposed", "fairly well decomposed", and "coarse textured" or "poorly decomposed" (POST, 1921; SUKACHEV, 1923; TACKE, 1930).

In areas subject to periodic overflow, organic detritus is enriched in silt and clay particles sedimented during inundations and giving rise to *muck soils.* In some instances such soils are formed in grassy swamps or marshes where sedges, cat-tails, and reeds release in decomposition a certain amount of mineral "earthy" matter which infiltrates into the organic residue. Ordinarily the muck layer contains 20 per cent or more of mineral material.

TABLE 7. — *Total Analysis of Moss, Sedge and Woody Types of Peat (Weighted Averages)*: —

TYPE OF PEAT	O.M.	SiO_2	N	P_2O_5	K_2O	CaO	Fe_2O_3 + Al_2O_3
	Per cent						
Bog-moss peat (Sphagnum)..	97.8	0.7	0.92	0.04	0.06	0.20	0.25
Brown-moss peat (Hypnum)	94.5	1.5	2.09	0.06	0.08	1.00	0.60
Sedge peat (Carex).........	95.3	0.9	2.91	0.10	0.15	1.95	1.00
Woody peat (Deciduous and coniferous)	94.5	1.7	2.05	0.11	0.12	1.41	1.37

Moss peat has the lowest content of nitrogen and mineral nutrients; sedge peat and muck, the highest. Woody peat occupies an intermediate position. Almost invariably moss peat has an extremely acid reaction; the reaction of other types varies from strongly acid to alkaline (ZAILER and WILK, 1907; MINSSEN, 1913; MILLER, 1918; WAREN, 1924; FEUSTEL and BYERS, 1930). Table 7 gives average values from total analyses of the most important peat materials (WILDE and HULL, 1937).

Although low moor soils are of numerous varieties, they have the same general morphological pattern. The profile consists of an organic surface layer of varying thickness (A_0), a black, partly mineral, partly organic "sapropel" layer (A_1), and a mineral gley horizon (G), sometimes darkened by infiltrated humates. The soils formed in lakes or swamps with hard water are underlain by a calcareous layer of *marl* or *bog lime,* accumulated by precipitation from solution, from animal shells, and carbonate secretions of algae. Organic layers of low moors in temperate regions attain a thickness of many yards; similar organic soils in tropics, however, seldom exceed a depth of 3 feet (VAGELER, 1933). The following descriptions illustrate the morphology of the more important types of low moor soils (DOKTUROVSKY, 1922; AVERELL and MCGREW, 1929; DACHNOWSKI, 1933).

Moss peat formed in stagnant Sphagnum swamp or "bog" supporting black spruce and tamarack:

A_0 23". Slightly decomposed fibrous remains of mosses of yellowish-brown color grading into more compact, dark brown, sedge-moss peat. Strongly acid.
A_1 5". Transitional layer of greyish-brown sand with some incorporated remains of sedges and aquatics. Acid.
G Bluish-green sand. Neutral.

Woody peat formed under northern white cedar and balsam fir in a locality with slow but continuous underdrainage:

A_0 36". Partly decomposed, brown to black remains of swamp trees, mainly white cedar, with many fragments of wood retaining their identity. Peat is slimy to the touch and has a strong, disagreeable smell of hydrogen sulfide. Strongly acid.
A_1 36 to 42". Plastic, wet clay high in organic matter, of a black color. Slightly acid.
G Wet sand with some gravel and varying amounts of clay, green mottlings, and agglutinations. Alkaline.

Muck formed under tag alder in an area subject to overflow:

A_0 3". Dark brown, partly decomposed organic matter of somewhat granular structure.
A_1 3 to 24". "Sapropel" layer; black, plastic and moist mixture of dispersed organic matter and clay, becoming dark or brownish-grey at the lower limits of the horizon. Slightly acid.
G Compacted gley layer of a silty clay texture with brownish and greenish mottlings. Slightly alkaline.

Moss peat of low moors support highly acidophilous tree species. Outstanding among them are black spruce, tamarack, Scotch pine, and dwarf birch. Woody peat is correlated with a wide variety of swamp conifers and hardwoods, such as species of spruce, balsam fir, white cedar, black ash, red maple, swamp maple, elms, and willows. Tropical woody peats support a particularly diversified cover. Muck soils are characterized by an abundance of alder, occurring in pure stands or in mixture with numerous water-loving species. Sedge peat supports marsh vegetation. Forest stands on all types of organic soils, as a general rule, attain but low or mediocre productivity (CAJANDER, 1913; KOTILAINEN, 1928; WILDE, 1933; FRASER, 1933; PRONIN, 1939). Plate 5 gives examples of characteristic ground cover vegetation of upland and. hydromorphic soils of northern forests.

Embryonic or Immature Soils: — The terms "embryonic" or "immature" soils are applicable to a great variety of forest-supporting substrata which are in their initial stage of weathering or differentiation into genetical horizons (Glinka, 1931; Marbut, 1935). Rock outcrops, skeletal debris of talus slopes, and "raw" gravelly or stony ridges of moraines are the most striking representatives of soils *in statu nascendi.* Other members of this group include soils of denuded slopes and recent deposits formed by water, wind, and gravity.

Although immature soils exhibit no "profile" in the genetical meaning of this word, they often have a substantial layer of forest litter (A_0), a more or less developed layer with incorporated humus (A_1), and a gley horizon (G); this is especially true of alluvial or stream-bottom soils. In time embryonic soils undergo the process of profile development and become "mature", provided this is not prevented by continuous denudation or deposition.

Embryonic soils are distributed throughout the entire forest region and are of particular interest in silviculture. In many cases, it is the forester's problem to act as a "soil-forming factor" and to convert by afforestation the profile of embryonic soils into its proper genetical morphology. The following discussion of embryonic soils is confined to the types of major silvicultural importance.

(1) *Rock outcrop soils:* — Within forest regions the occurrence of rock outcrops is limited to high mountains, steep slopes, and areas denuded by the action of glaciers. Root systems of trees clasp the rock surface and penetrate through fissures, thus changing barren strata into rock outcrop soils. In accordance with the petrographic composition, different varieties of rock outcrop soils are recognized, such as granitic, siliceous, ferromagnesian, and calcareous (Bowman, 1911; Emerson, 1920).

If conditions of climate and gradient permit, material weathered from the bed rock accumulates *in situ* as "mantle rock" or "residuum". In time, the weathered mantle may attain considerable depth and give rise to a productive and genetically developed residual soil.

As a general rule, rock outcrop soils support isolated pioneers or struggling stands of less exacting species. Some trees, however, are able to derive sufficient moisture and nutrients from slightly weathered rocks; in consequence, stands of a fairly high density and rate of growth may be found on such habitats. Species of spruce on granitic outcrops and species of pine on sandstone bluffs are striking examples. A number of mensurational analyses have shown a better growth of pines and other species on exposed rocks than on coarse outwash sands of the same petrographic composition (Pohle, 1904).

(2) *Stony and gravelly soils:* — The coarse colluvial detritus of talus slopes, cliff debris, rock falls, and avalanches differ but little in their effect on forest vegetation from rock outcrops. In some localities these rough deposits impart to the country-side a distinct beauty; in others they appear as "wounds on the face of the earth" and must be "healed" by the forester at a very high cost. In places colluvial deposits endanger transportation and water courses and their fixation requires special work by forest engineers and tree planters (Wang, 1903; Thiery, 1915).

(3) *Barren sands:* — Humus-deficient sands include recent products of wind and water erosion, such as blow sands, beach sands, and fans of streams and rivers. In some regions, sandy deposits, deprived of the stabilizing vegetative cover, form sand dunes; these attain a depth of several hundred feet and may advance at the rate of a hundred feet per year burying productive land and buildings in their path (KROODSMA, 1937).

Barren sands are practically free of mineral colloids and organic matter; they have but a minimum content of available nutrients, are subject to drought, and support sporadic stands of a few less exacting pines, willows, and cottonwood. Control of erosion is the chief reason for afforestation of these primitive soils.

(4) *Denuded soils:* — Soils of denuded areas vary in their properties depending upon the nature of the exposed subsoil. The hypothesis that erosion renews the fertility of the soil by exposing the unleached substratum has little foundation (BENNETT, 1939). As a general rule, the productivity of denuded soils is low, and they are reforested with difficulty.

(5) *Deluvial soils:* — Overwash, or in PAVLOV's terminology, "deluvium" (STEBUTT, 1930), is formed on the lower slopes of hills and mountains by the deposition of material eroded from the upper slopes. Deluvial soils, as a rule, have a greater depth, a finer texture, and a higher content of humus and nutrients than the residual soils of the upper denuded areas. In places the overwash covers "relic" or buried soils, and thus deluvial soils may have two or more superimposed humus horizons alternating with mineral strata. The occurrence of the more exacting tree species and a high rate of growth of the forest stands usually mark the areas of deluvial soils.

(6) *Alluvial soils:* — The action of streams in the post-glacial period produced three major types of deposits: stream bottoms, flood plains, and river terraces. *Stream bottom deposits* occur as narrow strips along creeks. A high content of organic matter and a ground water level near the surface, but not necessarily water stagnation, are common features of stream-bottom soils. *Flood plain deposits* are a result of periodic overflows. The soils of flood plains are sandy in the proximity of the stream but grade into loams or clays farther from the stream. This is because the velocity of flood waters decreases from the stream to the limits of the flooded area. The drainage is likely to be adequate near the stream, but impeded at a distance from it. The periodic inundations enrich flood plains in organic matter and soluble salts. *River terraces* are level or nearly level strips of land bordering flood plains. They result from the dissection of previous streambeds and are classified as "second bottom", "third bottom", etc. The soils of river terraces contain less organic matter and soluble salts and are better drained than flood plain soils.

Alluvial soils support a diversity of forest types, the composition and productivity of which are determined by texture and drainage. Stands of bald cypress, tupelo gum, and other hardwoods of Mississippi lowlands present one of the world's outstanding examples of forest cover on alluvial soils. Forests of stream bottoms provide food and protection for wild life and the preservation of such stands is essential from a conservation viewpoint (LEOPOLD, 1933).

Chapter V

FOREST COVER; ITS BIOLOGICAL STRUCTURE AND ITS RELATION TO ENVIRONMENT

> "As far as possible men are to be taught to become wise not only by books, but by the heavens, the earth, oaks, and beeches."
> "Great Didactics"
> by COMENIUS, 1632

Interdependence of Silviculture, Ecology and Soil Science: — It is generally agreed that the growth and reproduction of forests cannot be fully understood without a knowledge of soils. Just as truly, a comprehension of forest soil suitability or productivity cannot be acquired without an understanding of the biological nature of forest cover, its sociological structure, and the complex relationships that exist between the trees and their environment. This chapter summarizes briefly those fundamentals of modern silviculture, forest ecology, and dynamic pedology essential for obtaining a broader viewpoint and a more correct interpretation of the significance of various properties of forest soils.

Modern Conceptions of the Forest: — The forest is a tract of land covered with trees which grow close together, or, as one American has expressed it, "the forest is an over-production of trees on a certain area." This "over-production" of trees is an important factor of forest growth, the factor of sociability (PACZOSSKY, 1921). Trees growing far apart and trees growing close together differ in their height and diameter growth, size of crowns, form of stem, and quality of wood produced. The natural reproduction of isolated trees is exposed to adverse climatic influences, while the reproduction in a closed stand develops under the protection of a canopy. Trees in the open live their normal age, whereas most of the trees in a dense forest are eventually killed by their neighbours. In a young forest there may be as many as 50,000 seedlings per acre, while in a forest stand one hundred years old there may be only 100 trees per acre. Through this enormous rate of mortality, nature eliminates weak individuals incapable of competing with their more vigorous associates. If seedlings in artificial reforestation are planted too far apart, a true forest is not created, but rather an orchard of short, brushy trees, worthless as timber. There is no struggle for life in such plantations, and unfit specimens have a chance to grow and reproduce. Thus, tree planting which disregards the social aspects, tends to bring about a general degradation of the present stand, as well as degeneration of the future forest which may originate from inferior seed trees.

The intimate association of trees in forest stands entails not only struggle for life among both species and individuals (DARWIN, 1859), but also their cooperation in growth (MOROZOV, 1912). The planting of white birch and other pioneer trees to encourage the growth of spruce seedlings is a commonly quoted illustration of "cooperation" between tree species. Of equal silvicultural importance is the combination of pine and a soil conserving

understory of oak, beech, or hornbeam. Yellow birch, basswood, and a number of other species that never occur in pure stands, appear to be dependent upon hard maple or oaks which form the bulk of the forest. Optimum development of white spruce takes place only in association with tolerant hardwoods which provide shade and fertilizing litter.

The trees are the most outstanding but not the only constituents of the forest. Each forest stand is associated with shrubs, herbaceous plants, mosses, lichens, fungi, bacteria, protozoa, worms, insects, birds, mammals, and other animals. The occurrence of all these organisms is not accidental; their existence depends upon the food furnished by their associates. For this reason, the forest is referred to as an association of mutually related plants and animals, called "Biocenose", "Biome", "Lebensgemeinschaft", "community" or "life unit" (Müller, 1878; Clements and Shelford, 1939). Competition or antagonism, commensalism, symbiosis, saprophytism, and parasitism are the basic forms of interrelationship (Braun-Blanquet, 1932) that keep all of the associated members in a state of "biological equilibrium". The disturbance of this equilibrium by man's activity may cause grave consequences. In localities where wolves, foxes, and other predators are exterminated, the number of rabbits or other rodents may increase to such an extent as to arrest the natural, as well as the artificial regeneration of the forest. The destruction of shrubs and ground vegetation by grazing may induce an emigration of birds from the area. The absence of birds may permit the local multiplication of destructive insects, like the gypsy moth and sawfly, and the subsequent devastation of extensive forest tracts.

The distribution of both plants and animals is limited by the conditions of environment (Warming, 1895; Rübel, 1930; Lundegårdh, 1931). Certain species of plants and animals thrive and propagate in one physiographic medium, and struggle, degenerate, and die off in another. In this manner, the influence of environmental factors brings together the species adapted to more or less similar conditions of climate and soil. The resulting combinations of life-communities and physiographic conditions are called "life zones" (Merriam, 1898) or "geographical complexes". Forest stands of a uniform habitat are examples of such geographic complexes (Morozov, 1912; Rubner, 1925).

Trees planted in an unsuitable environment usually perish during the first few growing seasons. If such trees accidentally survive, they do not produce viable seed and are doomed to gradual extinction. Interference with the normal metabolism of seedlings is likely to occur because of the absence of some associates of the soil-forest complex, for instance mycorrhizal fungi or other useful organisms. The absence of hyperparasites, combined with unfavorable environmental conditions, may convert the struggling plantations into dangerous breeding centers for pathogenic fungi and harmful insects. The wholesale destruction of Norway spruce plantations in central Europe by nun moth and bark beetles serves to illustrate the fate of reforestation violating the environmental requirements of tree species (Nechleba, 1923).

Physiological Properties of Trees as Related to Environmental Conditions: — Through evolutionary processes, trees acquire certain

characteristics impressed upon them by environmental factors, *viz.*, light, temperature, and moisture. Knowledge of these characteristics of different tree species, particularly tolerance to shade, temperature requirements, resistance to frost and drought, and ability to withstand an excess of water, forms an important prerequisite to the study of soil-forest relationships.

Light requirements: — From the time of seed germination, trees continually struggle with their neighbors for light. If a tree is suppressed by its neighbors and does not obtain sufficient light, it either dies or barely exists, producing but little wood. In northern forests suppressed spruce trees may be one hundred years old and only one-half inch in diameter and three feet high.

The minimum amount of light required for survival varies with different species. Some trees are satisfied with a very small amount of light, and their seedlings may survive under the dense canopy of a mature stand. Such trees are the *tolerant* species. Other trees require a considerable amount of light, and their seedlings can develop only under a sparse canopy or in open areas. These trees are the *intolerant*, or *light demanding* species (Gayer, 1876).

In the constant struggle of trees for existence, the more tolerant species have a better chance to win the battle and to displace intolerant species. As a result, the degree of tolerance to a great extent determines the ultimate composition of natural forest stands, and must be considered in silvicultural cuttings and in reforestation.

Intolerant trees grow faster during their youthful stage than the tolerant species. On the whole, however, the tolerant species produce considerably higher yields of timber. The intolerant species are, in general, frost and heat resistant, and may be planted in the open; tolerant species are subject to damage by frost and sunscald, and can be planted only under a protective canopy. Below are listed some of the more important tree species, according to their degree of tolerance (Mayr, 1909; Morozov, 1912; Toumey and Korstian, 1928; Baker, 1934).

a. *Very Tolerant*	b. *Tolerant or Intermediate*	c. *Intolerant*
Yew	Douglas fir	Ponderosa pine
Hemlock	Silver fir	Austrian pine
White fir	Noble fir	Scotch pine
Balsam fir	White pine	Jack pine
Engelmann spruce	Loblolly pine	Lodgepole pine
Sitka spruce	Pitch pine	Longleaf pine
Norway spruce	Red pine	Shortleaf pine
White spruce	Yellow birch	Larch
We. red cedar	Chestnut	Tamarack
No. white cedar	Walnut	Alder
Redwood	Hickories	Aspen
Beech	White ash	Paper birch
Hard maple	Tulip poplar	Cottonwood
American elm	White oak	Black locust
Basswood	Red oak	Willows

Light conditions are peculiarly related to the nutrient requirements of trees (Gast, 1937*b*). The greater the amount of light, the less the amount of mineral nutrients required to produce the same yield of timber, other conditions being the same. Vice versa, the greater the amount of available nutrients, the more overshading the species can stand. Species which grow on sandy soils with a low content of available nutrients are highly light-demanding, *viz.*, scrub oaks, jack pine, Scotch pine, paper birch, aspen, and willows. On the other hand, tolerant species such as spruce, fir, hard maple, and basswood require a fair amount of either organic or mineral nutrients.

Temperature requirements: — Temperature determines the growing season of trees, *i.e.*, the period during which wood is produced. A certain amount of heat

throughout the growing season is necessary for the development of viable seeds; hence, for the existence of tree species (MAYR, 1909). Extremes of heat and cold may kill the trees by coagulating the protoplasm or precipitating the proteins.

The temperature requirements of trees vary considerably within the same species. However, three broad groups of trees in relation to temperature requirements may be recognized:

a. *Megathermic trees,* requiring a warm climate and long growing season: palms, laurels, magnolia, southern oaks, tupelo gum, redwood, bald cypress, slash pine, longleaf pine, and other southern pines.

b. *Mesothermic trees,* growing in a temperate climate: chestnut, oaks, hickories, walnuts, tulip poplar, beech, maples, basswood, ash, elm, white pine, red pine, western yellow pine, hemlocks, Douglas fir, and some true fir species.

c. *Microthermic trees,* tolerating a cold climate and short growing season: aspen, birch, alder, willow, mountain ash, jack pine, Scotch pine, lodgepole pine, spruces, larch, alpine fir, and mountain pines

In general, megathermic or thermophilic species develop in regions characterized by a high activity of soil organisms and rapid decomposition or "mineralization" of organic remains. Microthermic species develop in regions characterized by a low activity of soil organisms, accumulation of raw humus, and leaching of salts from the upper soil layers. Consequently, the thermophilic trees feed primarily on mineral salts, whereas the microthermic trees are able to derive their nutrients from the organic colloids of raw humus, and are sometimes called "raw humus species".

Moisture requirements: — All the life processes of trees go on in water solution, and as soon as the water supply is exhausted, the trees wither and die. More than any other factor, water affects the distribution and growth of forest vegetation (WARMING, 1895). According to their water requirements, trees are divided into the following groups:

a. *Xerophytic* or *drought-resistant trees* survive with small amounts of available water. Typical examples of this group are jack pine, Scotch pine, longleaf pine, red cedar, scrub oaks, black locust, and Russian olive.

b. *Mesophytic trees* require a fair amount of moisture. This group embraces the great majority of tolerant hardwoods and conifers.

c. *Hygrophytic* or *moisture-loving trees* are, as a rule, very sensitive to drought and can tolerate a high content of moisture. Typical trees of this group are: black ash, some willows, river birch, alder, tupelo gum, most of the spruces, white cedar, tamarack, and bald cypress.

Drought-resistant species are usually confined either to dry regions or to sandy soils, whereas moisture-loving species are confined to humid regions or to heavy and moist soils.

Relation of Forest Vegetation to Soils: — The relationship between soils and forest vegetation has long been known to rural people. The early settlers of the Lake States region, for example, considered "white pine soils" as fair pasture, "Norway pine soils" as mediocre fields, and "jack pine soils" as soils unsuited for agricultural use (MAYR, 1890). At present, the expression "hardwood land" commonly refers to a good agricultural soil, whereas the expression "hemlock land" refers to a leached soil of questionable productivity. "Balsam flats" in the farmer's mind are associated with heavy, moist, and cool soils, suitable for grazing rather than for cultivation.

"In the Southern States", writes HILGARD (1906), "the classification of uplands into 'pine lands' and 'oak lands' is universal, and is associated with certain limits of valuation, both by assessors and purchasers. With each of these two classes, however, there are well-defined gradations of cultural value according to the kind (species), *e.g.*, of pine or oak that occupies the ground, either alone, or in mixture with other trees whose presence or ab-

sence is considered significant. In the case of 'bottoms' or alluvial lands, corresponding distinctions and classifications obtain; we hear of hickory, beach, gum, and cherry bottoms, hackberry hummocks, etc., each name being associated with certain cultural values or peculiarities well understood by the farming population."

Numerous commonly used terms such as "cedar swamp", "leatherleaf bog", "muskeg", "quagmire", "pocosins", "flatwood", "pine barrens", and "chaparral", express the characteristic features of both soil and its associated vegetation, and thus reaffirm the correlation that exists between soil and floristic cover. In the initial stage of ecological research, the folk terminology served as a valuable guide to soil scientists and foresters and helped to establish a number of important relationships between soil and vegetation (KRUEDENER, 1927). With the accumulation of knowledge, however, the students of forest soils came to realize that not all of the relationships between the soil and tree growth are necessarily obvious, but may be concealed.

Obvious Relationships: — An obvious relationship may be illustrated by the following examples: Jack or Scotch pine on sandy soil; hard maple or basswood on heavy soil; alder on muck or wet soil. Relationships of this kind are evident even to a non-technical man who has had some contact with the forest, and can easily be explained by assuming that jack and Scotch pines require the good aeration of sandy soil, maple and basswood the abundant mineral nutrients of heavy soil, and alder the moisture of a swamp soil.

Concealed Relationships: — Many species of trees occur on soils which vary greatly in their texture, drainage, and fertility. For instance, white pine or aspen occur on sandy as well as on heavy soils, on well drained as well as on poorly drained soils, on soils high in nutrients as well as on soils poor in nutrients. A careful investigation shows, however, that white pine avoids the poorest sandy soils, such as wind-blown sands, the soils of recently burned areas with a low content of humus, soils of extreme reactions, and bogs with stagnant water. If the study is not limited to the distribution of trees alone, but considers also the rate of growth (WESTVELD, 1933), and intensity of natural reproduction, it will be found that the optimum growth of white pine is confined to the well aerated heavier soils with a fair content of moisture and available nutrients. Moreover, white pine, or any other species, exhibits on different soils dissimilarities in the form of its stem, crown, and root system. HILGARD (1906) describes as many as four distinct morphological varieties of post and black oaks adapted to upland loams, sandy ridges, flatwoods, and black calcareous soils of the South.

Ecological Amplitude: — The occurrence of any tree is determined by the "ecological amplitude" of the species. Ecological amplitude refers to the range of environmental conditions in which a certain species can exist. The alder is limited in its distribution to soils with a high content of moisture, and hence has a narrow ecological amplitude. White pine or aspen survive under a wide range of conditions, and have a wide ecological amplitude. Aside from the ability of trees to survive under different con-

ditions of environment, their distribution depends upon their ability to compete with other vegetation. In this respect the weight of seeds, ability to produce sprouts, and the light requirements of trees are the important properties which determine the relative success of each competing species. Aspen, for example, can grow as well as hard maple on a well drained silt loam soil. Yet, aspen is a light demanding tree, whereas hard maple is a tolerant tree. The young reproduction of maple can develop under the crowns of aspen, but the aspen cannot grow in the shade of the hard maple canopy. Hence, hard maple will eventually crowd out the aspen, and will form a pure maple stand. The same relationships are observed in the cases of light demanding jack pine and tolerant white pine; light demanding paper birch or pin cherry and tolerant yellow birch and hemlock; light demanding European birch and tolerant Norway spruce.

Mass Action of the Forest: — The occurrence of a tree species on a specific type of soil depends to some extent on the composition of the forest of the entire region as well as on the size of the area occupied by the soil type. For example, a few acres of heavy soil in a region of sandy soils would hardly support hard maple or hemlock, but more likely stands of pine, since most of the region is occupied by the pine species.

Sometimes certain species may temporarily occupy an area after the original forest stand has been destroyed through accident. Numerous tamarack swamps in the Lake States at present support black spruce, the tamarack having been destroyed 50 years ago by saw-fly.

Modifying Influence of Climatic Factors: — Climatic conditions radically change the suitability and productivity of soils having the same textural and mineralogical composition. A sandy soil of granitic outwash may be a satisfactory site for spruce in the cool and moist climate of Alaska, but is unsuitable to the same species in the continental climate of central Wisconsin. Austrian pine in Bohemia has a comparatively short growing season and shows signs of starvation on soils low in nutrients; however, the same species grows satisfactorily on barren sites in the Mediterranean region, where its growing season is considerably longer.

These examples are sufficient to illustrate the fact that climate and soil are two inseparable growth factors. In consequence of this, all classifications of the various soil properties are valid from an ecological standpoint only within a specific climatic region. The maxim of Pfeil, "no general rules in forestry", was not intended by its author to introduce into forest management a spirit of anarchistic disorder, but to protest against unjustified generalizations based on local experiences — generalizations which disregarded the modifying influence of environmental factors and contaminated silvicultural theory with an untold number of controversies.

Forest Succession: — Logging and forest fire may temporarily change the natural distribution of tree species. The forest cover of cut-over or burned-over areas rarely consists of the same species that previously dominated the area. As a rule, logging or fire is followed by the development of temporary stands of so-called pioneer species. The pioneer species are usually light demanding; they have low nutrient requirements and can with-

stand frost and endure sunscald. Typical pioneer species are: scrub oaks, aspen, paper birch, grey birch, pin cherry, jack pine, Scotch pine and many other pines (Morozov, 1912; Clements, 1916). Under favorable climatic conditions, however, some tolerant or semi-tolerant species, such as Norway spruce, white fir, Douglas fir, and even balsam fir may act as pioneers.

When the reproduction of pioneer species reaches the age of 20 or 30 years, tolerant species, such as white pine, spruce, hemlock, hard maple, and yellow birch, begin to develop under the protection of pioneer crowns. The tolerant species gradually suppress the pioneers, which die off as soon as they are over-shaded by the tolerant trees; thus, the temporary or pioneer stand is replaced by the permanent forest stand. This process is called local forest succession.

Besides local successions, the forest shows a general succession, or a general movement toward a few climax formations. The climax formations include a few tolerant species, which are best adapted to the climate and soil of the region. For example, in some portions of the Lake States region the climax formation is a mixture of hard maple, beech, basswood, yellow birch, and hemlock (Weaver and Clements, 1938).

Succession and Soil Development: — The general movement of forest toward the climax is closely related to the gradual changes which take place in the soil profile. Soils are subject to progressive weathering, and in the long run tend to increase their colloidal content and water-holding capacity. Simultaneously, the xerophytic species of light soils are gradually replaced by the mesophytic species of heavier or moister soils. The accumulation of humus and podzolization of the soil have a similar effect, since both of these processes tend to increase the water-holding capacity of soil.

Importance of succession in reforestation: — The succession of tree species, particularly the local succession, has considerable significance in reforestation practice. Some light sandy soils of North America supported a number of virgin white pine stands of fairly good growth. This fact led to the inference that light soils were suitable for planting white pine. However, white pine plantations on such soils have either perished, or show very poor growth. This happened because reforestation practice has disregarded the principles of natural succession. White pine of the virgin forest invaded the light sandy soils at a time when the soil was covered by a thick layer of duff, and was protected by a canopy of pioneer crowns: *i.e.*, in an environment greatly different from that of a cut-over area. In recent times it has been proven on numerous occasions that the survival of white pine is greatly increased if the forest succession is imitated by previous planting of pioneer species. European practice has gone so far in this direction as to plant white birch as a nurse crop to protect the subsequently underplanted spruce from direct exposure, while mugho pine is planted along with the spruce to provide a layer of litter.

Productivity and Soil Dynamics: — The recent teachings of pedologists present soil as a "continually changing medium which is a function of the geological substratum, environmental influences, and activity of organisms" (Stebutt, 1930). In the light of this definition, the soil and forest stand are not two independent bodies, but are integrated parts of the same dynamic system. Therefore, the composition and productivity of a forest soil is affected by all the modifications of environment which may result from man's activity, *viz.*, logging or thinning of stands, planting of trees,

burning of slash, removal of litter, pasturing, and so forth. Studies of forest soils have actually shown that even minor silvicultural treatments almost immediately bring marked changes in the composition of the soil (KRAUSS, 1911; MEJSTŘÍK *et al.*, 1929).

Growth Factors: — The rate of wood production results from the influence of two broad, not sharply delineated groups of growth factors: *primary* or physiographic factors, and *secondary* or biogenic factors.

The primary factors comprise general climate or macroclimate, topography, drainage, soil texture, and mineralogical composition of soil. Secondary factors of growth include inherent properties of the forest stand and the influence of the environment it creates, especially influences of the microclimate under the forest canopy, forest litter and associated flora and fauna.

The physiographic factors have a rather constant value and represent a certain potential ability of land to produce timber, or the *potential productivity* of the forest soil. The potential productivity is estimated by means of a soil survey or soil analysis and is used in conjunction with yield tables as a basis for land appraisals and calculation of the financial possibilities of reforestation (WILDE, 1929*c*).

The yield of wood actually produced by a stand at a certain age is a concrete expression of all measurable and nonmeasurable factors of forest growth, and represents the *actual productivity* of a forest soil. In practice, the actual productivity is determined by measuring the age, heights, and diameters of trees on sample areas, and by estimating, with the help of volume tables, the amount of lumber, pulpwood, or firewood in board feet or cords produced per unit area. The actual productivity is of prime importance in evaluation of forest property, taxation, and calculation of the annual cut in forests managed on a sustained yield basis.

It is obvious that forest stands on soils of the same potential productivity may show considerable variation in their rate of growth. These variations may result from inherited weaknesses of the stand or may be due to incidental injuries by frost, sunscald, drought, and excessive rains. Improper planting, planting unreliable stock, removing litter, pasturing the forest stand, and other man-caused disturbances may also be responsible for poor growth on soils having a high potential productivity.

Correlation of Soil and Rate of Growth: — Since the productivity of forest land is influenced by a great number of incidental factors, no direct correlation between the soil and forest need be expected in any individual case. At the same time, a study of a considerable number of forest stands, growing under similar soil conditions, reveals the dominating influence of soil upon the rate of forest growth. In such studies, the accumulated data for each soil type are subjected to statistical treatment (ILVESSALO, 1923). Such treatment eliminates all incidental yields, falling outside the limits of the standard deviation, and establishes the average rate of growth which may be generally expected on the soil type in question.

Chapter VI

PHYSICAL PROPERTIES OF FOREST SOILS

Soil Texture: — Soil material may be divided into two fractions: a coarse fraction and a fine fraction. The coarse fraction includes particles larger than 0.05 mm. in diameter, *viz.*, stones, gravel, and sand; the fine fraction includes particles smaller than 0.05 mm. in diameter, *viz.*, silt and clay. The separation of these two fractions is made by shaking soil with water and allowing the suspension to settle. After one minute, the coarse soil particles have settled, whereas the fine soil particles stay in suspension. The relative amounts of the coarse and fine soil materials determine soil texture.

The coarse soil material represents the "skeleton" of the soil; its function is largely limited to the physical support of plants, and it plays a minor part in plant nutrition. The fine soil material is the active portion of the soil, which through its absorptive and nutritive properties fulfills manifold ecological functions. It is the carrier of life in the soil, or as STEBUTT (1930) says, it is the "soil protoplasm."

The Effect of Soil Texture upon Forest Growth under Natural Conditions: — The ability of soil to retain water depends upon the amount of silt and clay present; the higher the amount, the greater is the soil moisture content, other conditions being the same. Because the soil pores are filled with either water or air, an increase in the fine soil material and subsequent increase in soil moisture often leads to a decreased soil aeration. Finally, the fine particles are the chief source of soluble substances which serve the trees as nutrients. These effects of the textural properties of soils are frequently reflected in the composition and the rate of growth of forest vegetation (KRUEDENER, 1927). In general, soils with a low content of fine soil material, *i.e.*, sandy soils, support only trees which have low requirements for moisture and nutrients, such as pines, scrub oaks, white birch, and aspen. On the other hand, soils with a high content of fine particles, *i.e.*, loam soils, support trees which have high requirements for moisture and nutrients, such as species of spruce and fir, hard maple, basswood, elm, and white ash (HAIG, 1929; SCHOLZ, 1931; COILE, 1935; HOSLEY, 1936).

In the virgin forest, however, there may be found many instances where the correlation of soil texture and forest growth is masked by the influence of other factors, especially by the ability of forest stands to modify the environment. Through a succession of pioneer species, forest stands tend to adjust the soil to the requirements of trees which compose them. For example, cut-over sandy soils of the northern United States are suitable only for jack pine, or at best, for red pine. As soon as these species become established, they moderate the extremes of temperature with the canopy of their crowns, and accumulate humus which increases the water-holding capacity and supply of plant nutrients. Thus, they create conditions suitable for the establishment of white pine or hemlock, which may gradually replace the pioneer species. Similarly, the modifying influences

*of other pioneer forest stands diminish the significance of soil texture and allow more exacting species to succeed on soils with a relatively low con*tent of fine particles.

Planting of Trees on Soils of Different Texture: — In artificial reforestation, the soil of a cut-over or burned-over area has no protection from wind and sun. Such soils, as a rule, lack the layer of forest litter, and their nutrient content is considerably depleted. Under these conditions, the fine soil material becomes the decisive factor in the successful establishment of planted seedlings. On the basis of observations of plantations on well-drained soils of Wisconsin, WILDE (1935) suggested a textural classification of soils in relation to planting possibilities (Table 8).

TABLE 8. — *Relation of Soil Texture to Tree Planting:* —

Percentage of fine material	Soil Class	Reforestation Possibilities
Less than 5	*Sandy grit*	No profitable reforestation except in cases of wind erosion control.
5-10	*Sand*	Highly light-demanding pioneer species, such as jack pine and red cedar.
10-15	*Loamy sand*	Highly and medium light-demanding pines, chiefly red pine, Scotch pine, and jack pine.
15-25	*Sandy loam*	All pines including the semi-tolerant white pine.
25-35	*Light loam*	Conifers and hardwoods with medium requirements for moisture and nutrients, *viz.*, white pine, European larch, yellow birch, white elm, red oak, shagbark hickory, black locust.
35 or more	*Heavy loam*	Conifers and hardwoods with high requirements for moisture and nutrients; white spruce, Norway spruce, white cedar; white ash, basswood, hard maple, white oak and black walnut.

Because forest soils are not always uniform in their composition, the determination of soil texture should embrace the entire soil profile to the depth of probable root penetration. If the surface soil grades with depth into coarser material, it is necessary to be conservative in the choice of trees for planting. For instance, if a surface layer of sandy loam is only 10 inches deep and grades into coarse sand, it is better to plant red pine instead of white pine. Similarly, a 15-inch deep silt loam underlain by stratified sand and gravel, should be reforested to white pine rather than to hardwoods or spruce. If the surface soil is underlain by a heavier substratum, greater freedom can be exercised in the selection of species. The depth to the fine-textured layer, as well as the rate of root penetration, however, should be given due consideration. In planting a light loam soil underlain at a depth of two feet by a heavy glacial till, spruce may well be given preference instead of white pine. On the other hand, a coarse sandy soil, underlain at a depth of four feet by clay, cannot be reforested with spruce since it will take a number of years before the roots of the spruce seedlings will be able to reach the capillary water and nutrients of the clay layer; cottonwood, elm, and other species with rapidly growing root systems may be a desirable choice on such a soil. The fact should not be overlooked that some subsurface layers, such as a hardpan in podzols and a calcareous stratum in grood soils, may exert a detrimental physical or chemical effect upon the growth of seedlings.

The planting possibilities depend not only on textural characteristics of soil, but also on many other factors, such as ground water level, petrographic composition of soil, content of organic matter, and reaction. The adaptation of species to soil also varies greatly under different climatic conditions. Therefore, the knowledge of planting possibilities is to a great

extent a matter of local experience, derived from observations of both the natural distribution of trees and the growth of plantations.

Soil Texture as a Factor in Cuttings and Thinnings: — A knowledge of soil texture is essential in thinnings and selective logging because textural properties determine the intensity of cutting and the choice of tree species which should be favored. The heavier the soil, the lighter should be the cutting in order to control the competition of weed species. In thinning an oak stand on soil containing 10 per cent of fine material, as much as 80 per cent of the timber may be removed for the purpose of under-planting with pines; an oak stand on soil having 30 per cent of fine particles should be thinned not more than 40 per cent in underplanting with spruce. An attempt to convert, by partial cuttings, a hardwood stand into pine forests on soil of heavy texture would meet with little success, because on such soil the intolerant pine seedlings would be suppressed by the sprouting hardwoods. On the other hand, it would not be wise to protect spruce or other exacting species on soils which have less than 25 per cent of silt and clay in selective loggings; such species will not produce a satisfactory yield of timber on light soils.

Importance of Soil Texture in Forest Nurseries: — The soils of forest nurseries should have an adequate content of soil colloids to insure a sufficient and stable supply of water and nutrient salts. On soils with a low colloidal content, nursery stock may be adversely affected by extreme fluctuations in moisture and nutrients even though such are provided periodically by artificial irrigation and application of liquid fertilizers. On the other hand, nursery soils with a high content of mineral colloids present several difficulties. Heavy soils are usually water-logged in the spring and late fall, and nursery stock is often damaged by heaving. Such soils remain frozen until late in the spring and may cause serious injury to roots during the lifting of stock. Certain complications are likely to be encountered on heavy soils in the control of parasites and eradication of weeds. Considering all aspects, the desirable content of the fine soil material of nursery soils ranges between 15 and 25 per cent.

The application of commercial mineral fertilizers is at present a common practice in maintaining the fertility of nursery soils, especially those of a sandy texture. In applying fertilizers, the introduced salts must be balanced in the soil by a certain amount of colloidal material. If fertilizers are applied to a soil of a low colloidal content, the soluble salts may soon be leached out by rains or artificial watering. In times of drouth, the moisture of sandy soils rapidly decreases through evaporation. As a result fertilizers are carried upward and accumulate at the soil surface. In this way, the concentration of fertilizer salts in the surface inch may increase from about 500 parts per million to several thousand parts per million. Salts in such a high concentration are detrimental to seedlings and often cause "burning" of the seedling roots. For this reason, sandy nursery soils treated with mineral fertilizers should be enriched in colloidal material by the addition of clay, peat, or forest litter, or the fertilizers should be added as a compost (Plate 6).

Determination of Soil Texture: — Among the numerous approaches

to the determination of soil texture, that suggested by Bouyoucos (1927) has been found as the most suitable for the needs of reforestation practice. Following a procedure for rapid determination (Wilde, 1935), the entire analysis can be completed within a few minutes directly in the field.

The soil is passed through a 20-mesh sieve onto a piece of paper. A sample of approximately 40 grams of sieved soil is taken with a measuring spoon. Special attention should be given to filling the measuring spoon completely by packing the soil and then striking off just level full with a spatula. The sample is placed in a 125 cc. flask with a wide neck and approximately 1 gram of dispersing agent (sodium oxalate) is added, using a small measuring spoon that is filled level full. Then water is added up to the 100 cc. mark. A rubber stopper is inserted and the flask is shaken vigorously 60 times by hand and then placed on a level surface. After exactly one minute, a tube 5.5 inches high and 1 inch in diameter is filled with some of the suspension to the 60 cc. mark. A small, specially calibrated Cenco-Wilde hydrometer is immediately floated in the suspension in the tube, and the reading is taken as soon as possible.

The maximum amount of the fine soil material which can be read on the scale is 35 per cent. If a content higher than 35 per cent is to be determined, only 30 cc. of the suspension are transferred to the test tube and diluted to the 60 cc. mark with water. The test tube is vigorously shaken, placed on a level surface, and the hydrometer is floated. The reading is multipled by two to give the approximate percentage of fine soil material. For more exact determinations, in soils containing more than 35 per cent of fine material, the measured samples should be dispersed in 30 cc. of sodium oxalate solution with a rubber pestle previous to their transfer to the shaking flask. In the majority of cases the content of fine material above 35 per cent has little significance in practical forestry work.

Since the temperature and quality of water used in analysis affect to a certain extent the hydrometer reading, the hydrometer, before analysis, should be placed in the test tube with pure water to check whether or not the water level and zero mark of the hydrometer correspond. In case the zero mark is higher or lower than the water level, the difference must be subtracted from or added to the final reading. The difference due to temperature and quality of water does not exceed two divisions of the hydrometer scale.

Soil Structure: — Soil structure is defined as the arrangement of individual soil particles (Baver, 1940). If soil particles, *i.e.* sand, silt, and clay, are not flocculated into aggregates, the soil is said to have a *simple structure;* if aggregated, the soil has a *compound structure* (Russell *et al.*, 1929). The formation of structural aggregates is caused by the action of electrolytes and colloids, freezing and drying of soil, and the activity of soil organisms and roots.

The structural features of forest soils may greatly modify the ecological significance of soil texture. The trees on puddled clay soils suffer, at least periodically, from an excess of water and deficient aeration. For this reason, non-aggregated heavy soils support predominantly saprophytic conifers. The roots of these trees remain largely within the surface layer of raw humus, and thus partly avoid the ill effects of poorly aerated mineral soil. Contrariwise, heavy soils coagulated into aggregates have more favorable conditions of aeration and support a wide range of hardwoods and conifers. In some instances, clay soils develop extreme porosity due to intensive aggregation and behave more like sandy than heavy soils. Soils of this kind sometimes support stands of jack pine, red pine, and other species which require a high degree of soil aeration. Lacustrine clays of the Superior series in the Lake States region furnish many examples of this condition (Wilde, 1932*b*).

Types of Structure Common in Forest Soils:—With regard to the structural features, different layers of forest soils may be classified into the following major types:

Single-grained:—An incoherent condition of the soil mass with no arrangement of the individual particles into aggregates; predominant in soils of sandy texture.

Massive or puddled:—A compacted or cemented condition showing no evidence of any distinct arrangement of the soil particles; common to soils affected by podzolization on impeded drainage. In many instances puddled structure is a result of grazing or agricultural misuse of the land.

Laminated or platy:—Aggregates form plates or layers 1/16 inch or more in thickness, oriented parallel to the soil surface, usually of medium to hard consistency; common in podzolic and strongly leached grood soils.

Crumby:—Aggregates of irregular shape, or a medium to soft consistency, 1/8 inch or larger in diameter; characteristic in humus layers of the mull type.

Granular:—Aggregates of more or less subangular or rounded shape, of medium consistency, varying in size up to 1/4 inch in diameter; common in humus layers of mull type, especially in those associated with melanized soils.

Nut-structured:—Compact aggregates, more or less rounded in shape, of medium to hard consistency, usually from 1/4 to 1 inch in diameter; outstanding in grood soils and soils of calcareous substrata.

Lumpy or cloddy:—Aggregates of irregular shape, of medium to hard consistency, 1 inch or larger in diameter; confined mainly to the deeper layers of heavy soils.

Porosity and Aeration:—The porosity of soils is determined by the space in the soil body not occupied by solids. Therefore, pore space (P), expressed in per cent by volume, is calculated from the real specific gravity of soil (S) and its apparent specific gravity or volume weight (V):

$$P = 100 \times \frac{S - V}{S}.$$

Porosity of forest soils varies from 30 up to 65 per cent. The coarse-textured soils usually have less pore space than fine-textured soils because of their smaller surface area and closer contact of the particles. However, puddled heavy soils, especially sandy clays, may have a porosity lower than that of sandy soils (Kopecký, 1928).

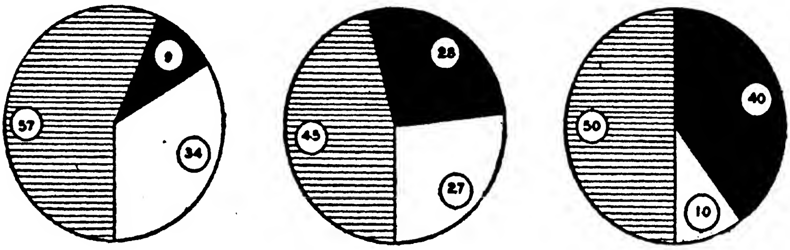
The pore space of soil is occupied by water and air; hence the porosity (P) and degree of soil saturation (W) determine the soil aeration (A):

$$A = P - W$$

It has been shown by several studies that the air content of soil exerts considerable influence upon the distribution and growth of forest vegetation (Hesselman, 1910; Burger, 1922; Romell, 1922; Němec and Kvapil, 1925; Semits, 1934). From a practical standpoint, the so-called "absolute air capacity" is of particular importance. This expression refers to the amount of air which is present in the soil after it has been saturated with water and allowed to drain for 24 hours. Some of the lowland conifers, such as species of spruce and fir, white cedar, and bald cypress, may tolerate an absolute air capacity as low as 7 per cent by volume without noticeable ill results (Wilde, 1929*b*). However, the upland hardwoods, particularly sugar maple and beech, deteriorate under such conditions. The air capacity in most upland hardwood and pine soils rarely falls below the 20 per cent level. In general, the optimum air content of forest soils lies in the proximity of 30 per cent. Figure 14 illustrates the relation of the solid, liquid, and gaseous phases generally found in forest soils of various textures.

The aeration is of great importance in soils of forest nurseries where seedlings are grown in close spacing. The requirements of different species, as well as soil porosity, establish the maximum allowable water content for nursery soils. If a soil has a porosity of 45 per cent, and 20 per cent is the minimum allowable air content, then the water content should not exceed 25 per cent for any appreciable length of time. As a rule, the air content of nursery soils should not be allowed to drop below 15 per cent.

The absolute air capacity, or the non-capillary porosity of soil, is correlated with the rate of water infiltration (WOLLNY, 1889; AUTEN, 1933). According to BURGER's (1926) observations, the soil from a productive forest stand with an air capacity of 17 per cent infiltrated 100 mm. of water in about 2 hours; a soil from forest barrens with a capacity of 5 per cent infiltrated the same amount of water in 45 hours.



1 2 3

FIGURE 14.—Relative contents of solids (cross-hatched), water (shaded), and air (white) in different forest soils at a depth of 2 feet; (1) Outwash Jack pine sand; (2) Nut-structured morainic silt loam under oak and hickory; (3) Podzolized lacustrine clay supporting white spruce and balsam fir.

Determination of the air capacity of soil finds its application in work with forest nursery soils. It is of great importance whenever the installation of tile drainage is proposed (KOPECKÝ, 1928). In some instances the air capacity may serve as an index of deterioration of soil by grazing or cultivation (BURGER, 1922; AUTEN, 1933).

Water Relations of Forest Soils:—Water occurs in soils in five principal forms: as gravitational, capillary, and hygroscopic water, as vapor, and as ground water.

Gravitational water:—The gravitational or "free" water fills the large non-capillary pores of the soil; it drains readily under the influence of gravity, and is largely responsible for translocation of soluble substances and mobile colloids. Gravitational water is readily available to plants, but it often excludes air from the soil and interferes with the oxidation processes and the respiration of roots. For this reason, gravitational water may at times be harmful to plant growth.

Capillary water:—Water in this form is held by surface tension in the soil capillary spaces and as a film around soil particles. The greater portion of capillary water is available to plants. Under the influence of surface tension the capillary water may move in any direction even against the forces of gravity. The movement in an upward direction is due to evaporation from the surface or absorption by the root systems. The rate and

distance of capillary movement depend upon the degree of soil saturation, the texture and structure of soil, and climatic conditions. It is much slower in stiff clays than in loose sandy soils, but the opposite is usually true in regard to the distance to which water may be drawn (WOLLNY, 1884). Within certain limits, capillary movement may benefit the growth of trees by supplying water to the roots from the deeper soil layers; it may also cause a loss of water due to evaporation from an exposed soil surface (FISHER, 1923; KEEN, 1931).

The maximum content of capillary water coincides closely with the "field capacity" and "moisture equivalent" of soil. Field capacity, according to VEIHMEYER and HENDRICKSON (1931), refers to "the amount of water held in the soil after the excess of gravitational water has drained away and the rate of downward movement of water has materially decreased." The moisture equivalent, a concept introduced by BRIGGS and McLANE (1907), expresses the amount of water held in the soil after it has been subjected by centrifuging to a force of 1000 times that of gravity.

Determination of moisture equivalent: — A simple method for the determination of the moisture equivalent was devised by BOUYOUCOS (1929); it is sufficiently accurate for practical soil work in forestry.

Fill a small Buechner funnel, 5 cm. in diameter and 2.5 cm. in depth, with air-dry soil that has been passed through a 2 mm. sieve. Compact the soil by gently tapping the lower end of the funnel against the table. It is important to maintain a uniform depth of soil. The depth used will give a weight of 40 to 85 grams, depending on the soil. Place the filled funnel in a beaker into which water is poured until it almost reaches the upper surface of the soil. After the soil has been soaked, place the funnel on a suction flask. Apply suction from a vacuum pump for 15 minutes after all the excess water on the upper surface of the soil has disappeared. Cover the soil with a tumbler containing a moist cloth to prevent evaporation during the time suction is applied. If the soaked soil swells above the edges of the funnel, level it off, after suction has been applied for one minute, by removing enough soil to make the upper surface even with the top of the funnel. At the end of 15 minutes, disconnect the suction flask, remove the funnel, and scrape the soil into a weighed receptacle. Weigh the soil before and after drying at 105° C. to determine the moisture content. The amount of water present, expressed in per cent, is the moisture equivalent.

Hygroscopic water: — Dry soil tends to absorb water molecules from the air until an equilbrium is established between the soil and the atmosphere. The absorbed molecules are held on the surface of soil particles (or in the micropores of the soil colloids) by the forces of adhesion. This fraction of soil moisture, referred to as hygroscopic water, may be driven off only at comparatively high temperatures and is unavailable to plants.

Because the surface area of soil is inversely proportional to the size of soil particles, fine textured soils hold a larger amount of hygroscopic water than the coarse textured soils. Based on this relationship, the maximum content of hygroscopically-bound water, or the hygroscopic coefficient, may be used as a measure of the soil colloidal content (MITSCHERLICH, 1923). The hygroscopic coefficient is also closely related to the entire fraction of soil water that is not readily available to plants and, hence, may serve as an index of the "physiological dryness" of soil. This condition is particularly serious in a region of light even though frequent precipitations; a light rain of but a fraction of an inch may be wholly consumed as hygroscopic

water and fixed capillary water by the dried surface layer of a heavy soil. In time this process may lead to the exhaustion of the available water supply in the entire root zone. Physiological dryness may account for the occurrence of pines and other xerophytic species on some soils of clay texture. For the same reason, certain types of peat are objectionable as fertilizers for forest plantings (FEUSTEL and BYERS, 1936; WILDE *et al.*, 1942; JAMISON, 1942). Top dressings of peat having a high hygroscopic coefficient were found to be detrimental even in soils of forest nurseries provided with artificial irrigation (WILDE and HULL, 1937).

The moisture content of soil at which plants permanently wilt is known as "wilting coefficient". The work of BRIGGS and SHANTZ (1914) indicated that the permanent wilting point is about the same for all plants on the same soil; it may be calculated approximately by dividing the moisture equivalent by the factor 1.84.

The pF value of soil: — The moisture equivalent, hygroscopic coefficient, wilting point, and other soil moisture equilibrium points can be conveniently expressed in terms of *p*F values, *i.e.*, the logarithm of the capillary potential, or the energy with which water is held by soils, expressed in ergs per gram (SCHOFIELD, 1935). The *p*F value of oven-dry soil is 7 and it decreases progressively with wetter soil. According to RUSSELL and RICHARDS (1938), the moisture equivalent occurs at *p*F 2.7, field capacity at about *p*F 3.2, and the wilting point at *p*F 4.2. A silt loam and a sand with a moisture content of 15 per cent are likely to have *p*F values of 4.0 and 2.0, respectively.

Water vapor: — An appreciable portion of the total soil moisture is made up of water vapor. In moist soils, the relative humidity of the soil air is always near 100 per cent (LEBEDEV, 1928). Below the wilting coefficient, the movement of moisture through the soil profile takes place largely in the form of vapor.

Water vapor moves from higher to lower pressure regions in accordance with the variations in the moisture and temperature of the soil. If the vapor enters a medium of low temperature, the dew point may be reached and condensation of the vapor will occur. Because of this, the soil on areas shaded by vegetation, boulders, or topographical variations, may be enriched during hot periods by water condensing on relatively cool surfaces. The importance of the condensed moisture in tree planting and silvicultural cuttings was strongly emphasized by SIGMOND (1924), who advocated the principle of rugged surfaces in handling both land and canopy of the forest. At a later date, the subject of water condensation was intensively investigated by LEBEDEV (1928), who has reported an amount of water condensed from the air in a single year equivalent to a precipitation of 70 mm. The same author pointed out that a cool and dry period, followed by a hot spell, may impoverish the deep layers of soil in moisture through the condensation of water at the surface and its subsequent evaporation.

Ground water: — The degree of soil drainage is intimately dependent upon the depth to the water-logged gley layer containing water that fills the tension-free pore spaces (OTOTZKY, 1905; TAMM, 1931). The upper limits of this zone of saturation are referred to as "ground water table". The zone between the ground water table and the margin of capillary effect is designated as "capillatum." The zone of ground water varies in thickness and is underlain by an impervious layer which was termed by WISSOTZKY (1927) "dry substratum" or "dead horizon of dryness".

As has been outlined in the discussion of soil genesis, the water table has a direct influence on the distribution and growth of forest vegetation. It is immensely beneficial to tree growth when located at a suitable depth, such as four or more feet, but becomes increasingly detrimental as it approaches the soil surface. The ground water delineates the depth of well aerated soil which serves as a medium for the growth of trees. With the exception of bald cypress, pitch pine, and a few other species (Hesselman, 1910; McQuilkin, 1935), the deficiency of air and presence of toxic reduced compounds prohibit the penetration of roots below the ground water table (Büsgen and Münch, 1929; Heyward, 1931; Sukachev, 1932; Woodroof, 1933). In this way, a shallow water table reduces the supply of nutrients actually accessible to the trees and creates other adverse conditions.

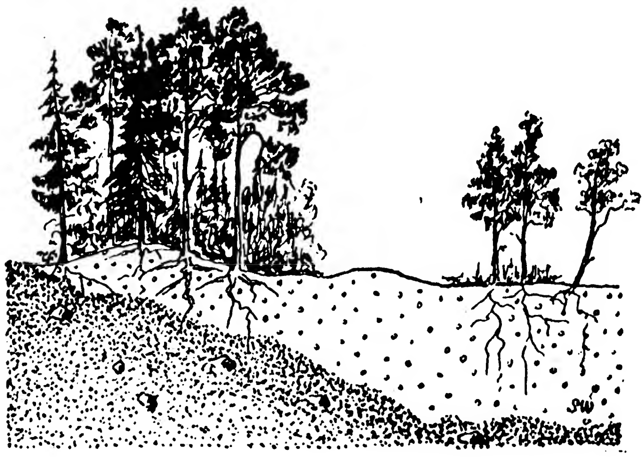
In the majority of cases, the occurrence of the ground water level is correlated with topographical features. The depressions have a high water level which permanently influences the soil and gives rise to *swamp forest;* the lower slopes are influenced by ground water periodically and support predominantly *lowland forest;* the elevated areas are not influenced by the ground water and are occupied by *upland forest.* This relationship, however, does not always hold true in nature. It is possible to find the ground water table at a lesser depth on the elevated plain than on the lower slopes or in depressions. This may be caused by the occurrence of impervious rock substratum, inter-layers of shale, or compact glacial till. Also, the perched water table or "verkho-vodka", as Russians call it,

Table 9.—*Correlation of the Ground Water Table with the Composition and Growth of Forest Vegetation in Wisconsin* (S. A. Wilde and D. P. White):—

Depth to ground water feet	Composition of forest stand	Yield at 100 yrs. cu. ft.*	Floristic site
	A. Podzol Region. Silty Clay Loams Derived from Granitic Drift		
1-1.5	Balsam fir, white spruce, some black ash and red maple. Understory of mountain ash, tag alder, willows and dogwood.	2,200	Sphagnum-Polytrichum-Carex-Equisetum site
2.0-3.0	Hard maple, rock elm, red maple, some basswood, yellow birch, balsam fir and white spruce Hard maple and basswood inferior.	3,500	Fern site
4.0-5.0	Hard maple, basswood, some white pine. Leatherwood and numerous other shrubs. Vigorous growth of sprouts.	4,800	Adiantum-Thalictrum-Hydrophyllum site
	B. Prairie-Forest Region. Silt Loams Derived from Calcareous Drift		
0.7-1.2	Lowland meadow.		Carex site
2.0-3.0	Bur oak, black oak, some red oak, aspen and box elder. Abundant hazelnut in understory.	1,900	Corylus site
4.0-5.0	White oak, red oak, some black oak, walnut, hickory, white ash.	3,200	Circaea-Amphicarpa-Paedera site

* Yields obtained by interpolation for fully stocked stands.

may occur in upland relief due to the impervious claypan layers formed by podzolic translocation of colloidal suspensions. The effect of the ground water table upon the growth of trees under different climatic conditions is illustrated by Table 9 (Wilde, 1940*b*).



Chapter VII

CHEMICAL PROPERTIES OF FOREST SOILS

"The soil is the chemical laboratory of nature in whose bosom various chemical decompositions and synthesis reactions take place in a hidden manner."

BERZELIUS

Significance of Soil Chemistry in Silviculture: — Opinions regarding the relative importance of the physical and chemical properties of soil to plant growth have varied considerably during different periods in the development of soil science. The pioneers in pedology — the agronomists — inherited from the rural people a body of basic information on the physical features of soils, such as classification of soils into sand, loam, and clay; wet and dry soils; deep and shallow soils; stony and stone-free soils, etc.

In the early days of scientific soil research, the pedologists concentrated their interest upon the chemical composition of soils, and pedology became synonymous with agro-chemistry. Some of the outstanding scientists of this period — BOUSSINGAULT, DE SAUSSURE, LIEBIG, LAWES, and GILBERT — established the basic relationships in plant nutrition and revealed the significance of artificial fertilization. However, the chemical analyses of soils of that time had been made largely by the use of strong hydrochloric acid, which extracts much greater quantities of nutrients than are actually available to plants (HALL and PLYMEN, 1902). For this reason a close correlation between chemical composition of soils and plant growth was not found. It was this state of soil analysis that led S. W. JOHNSON to proclaim in the American Journal of Science in 1861 that he "would rather trust an old farmer for his judgment of land than the best chemist alive" (HOPKINS, 1910). Consequently, the interest in soil chemistry declined, and attention was turned to the physical properties of soils. The study of soil physics, particularly of soil colloids, brought some valuable information regarding the cultivation and drainage of soils.

With an increase in theoretical knowledge, soil science again focused its attention on soil chemistry. This time, the work of soil chemists on the availability of nutrients to plants, their fixation, base exchange properties of soil and soil reaction showed a close relationship between these factors and plant growth. This newer knowledge, accumulated during the last 20 or 30 years, has solved many old problems of forestry and is rapidly becoming a basis of forest regulation, tree planting, and nursery practice.

The progress of soil chemistry owes much to studies of native vegetation and virgin soils, which had been advocated by HILGARD and his followers. One of HILGARD's statements (1906) relating to soil analysis is of particular interest to the student of forest soils: "Since the native vegetation normally represents the results of secular or even millenial adaptation of plants to climatic and soil conditions, the use of the native flora seems eminently rational. Moreover, it is obvious that if we were able to interpret correctly the meaning of such vegetation with respect not only to cultural conditions and crops, but also as regards the exact physical and chemical nature of the soil, so as to recognize the causes of the observed vegetative preferences, we should

be enabled to project that recognition into those cases where native vegetation is not present to serve as a guide; and we might thus render the physical and chemical examination of soils as useful practically, *everywhere*, as is, locally, the observation of the native growth."

Soil Reaction: — Acidity in solutions is due to an excess of H-ions over OH-ions; alkalinity to an excess of OH-ions over H-ions. Pure water contains equal numbers or concentrations of H- and OH-ions, and hence is neutral.

The concentrations of acidity and alkalinity found in soils and plant and animal tissues are relatively low, and the direct expression of the correspondingly low concentrations of H- and OH-ions in ordinary terms gives rise to fractional values which are inconvenient to express and use. To avoid this inconvenience, the *p*H scale and method of expression were devised by SÖRENSON (1909). The symbol "*p*H" refers to the intensity factor of acidity due to H-ions and also indirectly to the intensity factor of alkalinity due to OH-ions. The *p*H value derived under this system is simply the logarithm of the reciprocal of the H-ion concentration. Suppose the H-ion concentration of a solution is $\frac{1}{1000}$ gram per liter. What is the *p*H of this solution? The reciprocal of 1/1000 is 1000. The logarithm of 1000 is 3. Hence, the *pH* of this solution is 3. It so happens that the *p*H value for pure water is 7, and since pure water is neutral, a *p*H of 7 designates neutrality. The *p*H values are logarithmic functions of the reciprocal of the H-ion concentration, and hence the smaller they are, the greater the H-ion concentration, or the acidity. When the *p*H values become greater than 7, it follows from the law of mass action that the OH-ion concentration becomes greater than the H-ion concentration, and hence the solution becomes alkaline. The greater the value above 7, the greater the alkalinity. For example, a *p*H of 8 designates an alkalinity which is proportional or equivalent to the acidity at *p*H 6, and so on. The *p*H scale is well adapted for use when dealing with relatively small intensities and quantities of acids and alkalies such as found in soils and plants (TRUOG, 1918; OLSEN, 1924; ARRHENIUS, 1926; STOKLASA and DOERELL, 1926; KAPPEN, 1929).

The *p*H value of soil is determined either electrometrically (SNYDER, 1928) or, more commonly, colorimetrically, using rapid tests adapted for field work (WILDE, 1934; TRUOG, 1940).

Influence of Soil Reaction upon the Distribution and Growth of Forest Trees: — The reaction of the soil affects the distribution and growth of forest trees either directly through the influence of H- and OH-ions and the balance of acidic and basic constituents, or indirectly by affecting the physical condition of the soil, availability of nutrients, solubility and potency of toxic compounds, and activity of the beneficial and parasitic soil organisms (SAMPSON, 1912; NĚMEC and KVAPIL, 1925; AALTONEN, 1925; HARTMANN, 1925; WHERRY, 1927; FRANK, 1927; COILE, 1933; WILDE, 1934).

Mineral or organic soils more acid than *p*H 3.9 are characteristically covered with low shrubs, lichens and mosses. Trees that occur in such areas of heaths, ortstein podzols, or muskeg bogs are usually dwarfed. The trees of the tropical regions, however, are an exception and may tolerate a very high degree of acidity.

Soils of *p*H 4.0 to 4.7 support largely acidophilous conifers, such as Scotch pine, longleaf pine, European larch, tamarack, hemlock, and black spruce. The occurrence of deciduous trees is limited to birch, aspen and some species of alder. These very strongly acid soils are unfavorable to other trees because of poor physical condition, generally low availability of nutrients, and perhaps the toxicity of manganese and aluminum which are soluble to a considerable extent at a *p*H of 4.7 or lower (MAGISTAD, 1925).

Strongly acid soils of *p*H 4.8 to 5.5 are suitable for Norway spruce, white spruce, white pine and many other conifers, but not exacting deciduous trees. The low avail-

ability of certain nutrients, *viz.*, nitrogen in nitrate form, calcium, and phosphorous appears to be the chief reason for the inferior growth of most hardwoods on these soils (CLARKE, 1924).

Moderately acid soils of *p*H 5.5 to 6.5 are well adapted to the majority of conifers, particularly pines, and to northern hardwoods, including hard maple, basswood, rock elm, American elm, and red oak. Forest soils in this range of reaction are of the widest occurrence.

Circumneutral soils of *p*H 6.6 to 7.3 are characterized by high activity of micro-organisms, rapid humification and nitrification, and high availability of nutrients. Such soils usually are in a good physical condition and support predominantly deciduous species including exacting hardwoods, *viz.*, oaks, walnut, hickory, butternut, tulip poplar, beech, and red gum. Good growth of conifers is made chiefly by a few basophilous species, such as red cedar, white cedar, Austrian pine, ponderosa pine, piñon, and some species of fir. Most other conifers, particularly Norway spruce and Scotch pine, are often subject to fungous diseases on these soils.

Moderately alkaline soils of a *p*H 7.4 to 8.0 exert a decidedly unfavorable influence upon most conifers because of a high content of calcium and magnesium carbonates, low availability of iron, and often vigorous development of parasitic organisms. A high percentage of hardwoods on these soils is made up of less valuable trees, *viz.*, green ash, catalpa, box elder, hackberry and alder.

Strongly alkaline soils of a *p*H 8.1 to 8.5 usually contain an excess of soluble sulfates, chlorides, and carbonates, which are toxic to all forest trees. The native forest cover on such soils include dwarfed oaks, cottonwood, junipers, and piñon pines.

Very strongly alkaline soils of a *p*H higher than 8.5 usually contain toxic sodium carbonate. Such "solonetz" soils are occupied by halophytes and are unproductive from a forestry standpoint.

Occurrence of Soils with Critical Reaction: — The reaction of the great majority of forest soils lies within the limits of *p*H 5.0 and *p*H 6.5, a range favorable to the growth and propagation of a wide variety of tree species. The soils below *p*H 4.5 are largely confined to the regions of podzols and lateritic soils; in such regions soil reaction often is a factor of great concern in all phases of silvicultural practice. The soils of alkaline reaction, approaching *p*H 8.0, occur sporadically throughout the entire forest region, being associated with formations of limestone, dolomitic rocks, and calcareous deposits of glacial or alluvial origin. Alkalinity of soil is also of common occurrence in the transitional prairie-forest and desert-forest zones where the concentration of alkali salts produces in places an injurious reaction higher than *p*H 8.5. As a rule, the alkalinity of soil presents even more serious obstacles to silvicultural practice than acidity. Both states of reaction in their extremes greatly affect the management of forest nurseries, selection of planting sites or species to be planted, and silvicultural cuttings of forest stands.

Reaction of Nursery Soils: — The reaction of nursery soil influences the growth of seedlings which have specific optima of *p*H levels. The *p*H value also influences the development of many parasitic soil organisms, which may hamper the production of nursery stock. The reaction of soils determines the kind of fertilizers that should be applied. The growth of transplanted seedlings may be adversely affected by any considerable difference in the concentration of hydrogen ions of the nursery soil and that of the planting site.

In general, the desirable reaction of nursery soil lies between *p*H 5.0 and 6.0. For most coniferous species, which are subject to damping-off dis-

eases, the reaction is kept somewhat below *p*H 5.5, but not lower than *p*H 4.8; at this high degree of acidity the stock may suffer from the increased solubility of toxic compounds and low availability of nutrients. In raising most deciduous species, the reaction is maintained in the proximity of *p*H 6.0, but not higher than *p*H 6.5, otherwise conditions become too favorable for the development of root-rot fungi and other parasitic or undesirable soil organisms.

Soil Reaction and Tree Planting: — The extremely acid soils deserve particular attention in the selection of planting sites not only because of physiological effects of acidity upon the planted seedlings, but also because such soils are usually subject to severe leaching accompanied by the development of hardpan or similar impervious accumulative layers. These conditions greatly restrict the choice of suitable species and the methods of ground preparation.

Strong alkalinity of soils serves as warning that the site may be entirely unsuited to forest growth. However, in reforestation or afforestation of alkaline soils, consideration should be given to total alkalinity of the soil in addition to its *p*H value. Pure quartz sand with a mere sprinkling of calcareous dust may have a reaction of *p*H 8.0, due to the absence of buffering colloids, *i.e.*, the same reaction as a heavy calcareous clay derived from pure limestone. Actually, these two soils vary greatly in their content of carbonates and have an essentially different effect upon plant growth. Because of the generally low content of basic material, the alkaline sandy soils support in some instances acidophilous species, such as jack pine, which ordinarily avoids calcareous substrata.

The rule of thumb that may be followed in planting is that the conifers should neither be planted on very strongly acid (less than *p*H 4.5), nor on alkaline soils (more than *p*H 7.0), and the hardwoods on neither strongly acid (less than *p*H 5.5), nor strongly alkaline soils (more than *p*H 8.0). There are, indeed, a number of exceptions to this general rule. Yellow birch, for instance, is a hardwood species that does best on the strongly acid soils, and may survive even on very strongly acid soils. Hard maple may produce a high yield of timber on strongly acid, as well as alkaline soils, whereas white ash, hickory, walnut and some other exacting hardwoods may not even survive on strongly acid soils. White pine and Norway spruce may grow satisfactorily within a very wide range of reaction, from *p*H 4.5 to *p*H 7.0, and may survive on very strongly acid or alkaline soils, while red pine has a very narrow, sharply pronounced optimum between *p*H 5.0 and 6.5. Red and white cedar are the conifers that grow satisfactorily on acid as well as on alkaline soils.

The soil is not homogeneous in its *p*H value (Truog, 1918); in many cases the trees may escape the unfavorable influence of extreme reaction by feeding on the less acid or less alkaline portions of soil. This is especially true of seedlings produced by natural or artificial seeding; their roots after germination grow gradually into the soil and avoid regions of toxic H- or OH-ion concentration. In planting, however, the roots of seedlings are placed in the soil to a considerable depth and thus are subjected to any existing extremes of reaction. For this reason, the natural occurrence

of a species on a soil of a certain average reaction is not always proof of the suitability of this soil for planting with the same species.

Soil Reaction and Silvicultural Cuttings: — The significance of soil reaction in thinnings and selective logging has been generally overlooked in both forest writings and practice. Yet, this factor in many instances determines the success or the failure of silvicultural cuttings.

The reaction of the soil influences not only the distribution of trees, but also the distribution of the woody and herbaceous plants of the ground cover, *i.e.*, vegetation which often enters into vigorous and successful competition with natural tree reproduction. The composition of the ground cover and its potential capacity to occupy the selectively logged area vary enormously depending upon the *p*H value of the soil. This variation is frequently encountered in forest stands of approximately the same composition of overstory.

One example should suffice to illustrate this relationship. The ground cover of the hardwood-hemlock type on morainic loams with a reaction of *p*H 4.0 to 5.0 is made up of acidophilous plants of a saprophytic nature, such as yellow clintonia, club-mosses, bunchberry, Canada mayflower, partridge berry, twin flower, and creeping yew. This association includes no shrubs or herbaceous plants capable of competing with natural reproduction even when the stand is opened by an intensive selective cutting. An entirely different situation is found in hardwood-hemlock stands on morainic loams if the reaction of soil lies in the proximity of *p*H 6.0. The ground association on such soils is composed of sweet cicely, meadow rue, waterleaf, maidenhair fern, green briar, leatherwood, and numerous similar herbaceous plants and shrubs. An opening of such a stand by heavy cutting would terminate in the suppression of seed reproduction and invasion of the area by weeds and sprouts.

A high *p*H value of the soil favors the development of damping-off fungi which attack young conifers. This condition may present serious obstacles to the conversion of hardwood or mixed stands into a coniferous forest by means of partial cuttings and under-seeding. In stands established artificially, an insufficiently acid soil and associated pathogenic micro-population may wholly eliminate the possibility of natural regeneration. This is especially true in plantations of trees located outside of their native region.

A strongly acid reaction of the soil, indicating the probable presence of an impervious hardpan or claypan horizon, often dictates cutting methods which do not decrease the stability of stand against windfall.

The reaction of a soil is closely correlated with the rate of decomposition of organic remains, and has a bearing upon fire hazards and methods of slash disposal.

Plant Nutrients; Their Influence upon the Growth of Trees: — Early students of plants and their environment were inclined to over-emphasize the role of water in plant growth and paid little attention to nutrients. The noted text on plant ecology by Warming (1895) is a striking illustration of this trend of thought. The original Danish edition of this book considered exclusively the moisture conditions. Only after this work had been translated into German and revised by Graebner, did the influence of soil nutrients receive deserved attention.

The underestimation of the importance of plant nutrients was particularly marked in regard to tree growth. This attitude resulted largely from the

inference that trees growing in wide spacing utilize nutrients from an enormous volume of soil and increase the nutrient content of the surface soil layers through annual leaf-fall. At a comparatively recent date, careful studies have clarified the complex relationship that exists between soil nutrients and tree growth (Vater, 1911; Schwappach, 1916; Büsgen and Münch, 1929; Kuhnert, 1930; Leningen, 1931; Süchting *et al.*, 1933; Lang, 1934; Becker-Dillingen, 1937; Vagi, 1938). Plate 6 illustrates the effect of soil fertility factors on the growth of tree seedlings in a controlled environment.

If the seeds of trees, hardwoods as well as conifers, are planted on soils deficient in nutrients, their growth is arrested as soon as the supply of nutrients stored in the seed is exhausted. Species that have small seeds, such as spruce and elm, react immediately to a deficiency of soil nutrients. Species that have a large supply of plant food in the cotyledons, such as oaks and walnuts, show a rapid early growth regardless of soil fertility. Seedlings may survive on poor soils for a considerable number of years, producing little or no top growth, but concentrating all available energy upon the extension of the roots. As Liebig expressed it, "The roots search for the nutrients as though they had eyes . . . ." In case the starving seedlings obtain plant food at a greater soil depth, they may recover and gradually attain a satisfactory development, provided they do not succumb to parasites or adverse influences of environment during the period of starvation. Otherwise, the trees enter into a stage of chronic starvation which may be observed in natural stands, plantations, or nursery beds. Examples of nutrient deficiencies are presented by struggling stands of oak, black locust, spruce, and other exacting species growing on infertile soils, including those with an adequate supply of water. A deterioration of tree seedlings due to a lack of nutrients is well known to foresters who have had experience with permanent nurseries.

Of the many elements found in plant tissues, only a dozen or so are indispensable for the growth of trees. According to the somewhat outmoded findings of Sachs and Knop (Mazé, 1915), ten elements were recognized as essential for plant development: carbon, oxygen, hydrogen, nitrogen, sulfur, phosphorus, potassium, calcium, magnesium, and iron. The memorizing of these *major* elements is facilitated, as suggested by Cyril Hopkins, by writing their symbols in the following order — C. HOPK(I)NS CaFe Mg—and remembering that this is an abbreviated form of the expression—"See Hopkins Cafe—mighty good."

Carbon, oxygen, and hydrogen are usually present in nature in quantities far exceeding the needs of plants. Sulfur, calcium, magnesium, and iron are deficient only in comparatively rare instances. Nitrogen, phosphorus, and potassium are often deficient and are of chief practical importance in plant fertilization. In recent times it has been revealed that small amounts of the so-called *minor* elements are also necessary for the development of plants. Among these, boron, manganese, zinc, and copper appear to be of primary significance for the growth of trees (Willis, 1939).

With the exceptions of carbon, oxygen, and hydrogen, which plants obtain from water and air, the nutrients are supplied by the soil proper; in the case of legumes and some physiologically related plants, part or all of

the nitrogen may be derived from the air through the activity of symbiotic nitrogen fixing organisms.

Nutrients fulfill numerous physiological functions in the development of plants. They contribute to the material from which the protoplasm and cell walls are constructed; they influence the hydration of cell colloids, permeability of membranes, and osmotic pressure of plant cells; they provide the cell sap with buffering substances, regulate its reaction, counteract the effect of toxic ions, and act as catalysts or coenzymes. Each element fulfills in plant metabolism one or more specific functions.

Major Nutrient Elements: — *Nitrogen* is referred to as "the balance wheel in plant nutrition". It is an essential constituent of protein and protein-like compounds which are at the seat of all life processes. If nitrogen is deficient, plants show a stunted growth; their leaves or needles turn yellowish or reddish, and drop early; lateral buds die, and twig growth becomes stiff, woody, and reddish or brownish in color; the root system becomes fibrous and under-developed. The addition of a nitrogen fertilizer is followed by an almost immediate increase in vegetative growth and development of deep green foliage.

An excess of nitrogen results in an abnormally large and succulent growth of the aerial portion of the seedlings, and creates an unbalanced physiological condition. Thinning of the cell walls occurs, and the proportion of sclerenchymatic tissue is reduced; the stems become soft and tender and the leaves crinkled and sappy. As a result, the seedlings lose their resistance to drought, frost, and diseases.

Nitrogen-bearing organic substances in the soil undergo profound changes induced by microorganisms. The protein compounds are broken down into amino-acids, ammonia, and finally into nitrates. The latter two forms are the most important sources of readily available nitrogen for plants. The majority of forest trees, especially the conifers of saprophytic nature such as spruce, fir, and hemlock, have the ability to utilize the nitrogen of ammonia, and perhaps the less oxidized nitrogenous compounds. On the other hand, exacting hardwoods growing on well-drained soils, such as white ash, oaks, walnuts, and hickories, feed preferably on nitrogen in the nitrate form (Hesselman, 1916-17; Leiningen, 1925).

The content of total nitrogen in the surface 8-inch layer of virgin forest soil varies from about 0.1 to 0.3 per cent. The content of nitrates seldom exceeds 25 p.p.m. because of the high solubility of these compounds, their removal by leaching, or absorption by plants. Ammonia may accumulate in the humus layers of forest soils in amounts as high as 70 p.p.m.

The determination of total nitrogen by the Kjeldahl procedure (A.O.A.C., 1930) is one of the oldest and most reliable procedures in soil analysis. It is, however, somewhat laborious and is often replaced by the more rapid determination of organic matter. The results, expressed in percentages, are multiplied by .025 or another conversion factor to obtain an approximate measure of the total soil nitrogen. Because considerable variations in the carbon-nitrogen ratio occur in different soils, the conversion factors are usually established on the basis of local experience.

The contents of nitrate and ammonia nitrogen may be accurately determined colorimetrically by the phenoldisulphonic acid method (Harper, 1924*a*), and Nesslerization (Harper, 1924*b*), respectively. These methods may be replaced by rapid analyses (Morgan, 1941). The determination of both nitrates and ammonia in forest soils is confined to rather rare cases because of the marked fluctuations in amounts of these constituents.

Phosphorus is a constituent of the nucleus, and plays an important part in life processes, especially cell division and the development of meristematic tissues. It aids in the transformation of carbohydrates, and acts as a catalyst in respiration reactions. A high concentration of phosphorous is found in seeds; this is nature's assurance that the young plant will be amply supplied with this essential element.

In spite of these important functions of phosphorus in the growth of plants, its deficiency is not as readily observed as that of nitrogen, and may be easily overlooked. A poorly developed root system with coarse brown rootlets is the more common sign

of phosphate deficiency. A severe deficiency of phosphorus is revealed by a degeneration of lateral buds, restricted branching, and bronzing of leaves or needles. Narrow petiole angles and conspicuous purpling of the veins at the lower leaf surface are additional symptoms.

The application of phosphate fertilizers stimulates the assimilation of carbon dioxide, as well as a better utilization of nitrogen, potash, and other nutrients, and encourages development of lateral and fibrous roots. The development of a sturdy root system often prevents winter injury of young seedlings and assures rapid growth in the spring. This effect of phosphorus is of special practical significance in forest nurseries located on clay soils in which the roots tend to be under-developed, and the seedlings suffer from heaving.

Trees derive their phosphorus chiefly from calcium phosphate and organic phosphorus compounds; the phosphorus of iron and aluminum phosphates is also available in varying degrees to trees. The content of easily soluble or available phosphorus pentoxide (P_2O_5) varies in virigin forest soils from 10 to 200 p.p.m. Light-demanding pines and some deciduous pioneer species require only low contents of available phosphorus, such as 10 or 15 p.p.m., whereas maximum demands are made by exacting upland hardwoods. A content of available P_2O_5 of 100 p.p.m. is sufficient for most forest trees.

Available phosphorus is determined colorimetrically by extraction with a dilute acid solution and subsequent treatment of the filtrate with ammonium molybdate (TRUOG, 1930).

Potassium speeds up the assimilation of carbon dioxide, and is important in the formation and utilization of sugar and starch in plants, synthesis of proteins, and cell division. Under conditions of reduced sunlight, an ample supply of potassium partly makes up for the deficiency. Potassium is largely concentrated in the active regions of plants, *viz.*, young leaves and needles, buds, and root tips.

Deficiency of potash leads to the development of weak seedlings with a stunted root system and with soft and sappy leaves. In time, the leaves may become dull and scorched; they age prematurely, become bronzed, and die at the tips or along the edges.

The addition of potassium fertilizers increases the assimilation of carbon dioxide, facilitates the intake of water, and increases the utilization of nitrogen. This, in turn, increases the rate of growth and vigor of trees. Of particular importance is the influence of potash in counteracting the harmful effect of excessive nitrogen. Potash fertilizers in proper amounts seem to be especially effective in reducing root rot of older seedlings. Because resistance of seedlings to frost is directly related to the content of sugar, potash plays an outstanding part in the production of hardy nursery stock (WOHACK, 1930; KOPITKE, 1941)

Feldspars and micas are the chief original sources of potassium in soils; soils ordinarily contain from one to two percent of potash, and usually more than 90 per cent of this exists as feldspars and micas. The content of exchangeable or available potash (K_2O) in virgin forest soils varies commonly from 50 to 200 p.p.m. The amount of potash which satisfies the more exacting tree species is 150 p.p.m. As in the case of phosphorus, the pine species are satisfied with small amounts of potash, such as 25 p.p.m., whereas the upland hardwoods demand a higher content.

The determination of available potassium is commonly made by extraction with a normal solution of ammonium acetate and precipitation with sodium-cobalti-nitrite (VOLK and TRUOG, 1934).

Calcium influences the growth of forest trees directly as a plant nutrient, and indirectly by affecting soil reaction and other soil properties. It is particularly important in the development of roots and root hairs. Calcium pectate serves as the cementing material between cells like mortar between bricks, and plants deficient in calcium are characterized by weakness of tissue. Calcium aids in absorption of water and nutrients by favoring adequate permeability of the cell walls. It neutralizes toxic by-products formed in growth processes. A large portion of the calcium of plants is located in the leaves, especially in those of hardwood species (CHANDLER, 1939).

In soils, a proper balance of calcium tends to overcome the injurious effects of excessive amounts of sodium, potassium, magnesium, aluminum, manganese, and other

constituents which in the absence of calcium may become toxic to the plants. Development of soil microorganisms depends greatly on the supply of calcium. The formation of either raw humus or mild humus is closely associated with the calcium content of soils.

A deficiency of calcium brings about stunted growth and discoloration of the roots. It may also cause a brown spotting of leaves. Under natural conditions, a deficiency of calcium for tree growth is not common.

Calcium is abundant in limestone, basic or ferro-magnesium rocks, and many minerals. The amount of exchangeable or available calcium varies in forest soils from 400 to several thousand parts per million, depending upon the reaction and the base exchange capacity. With the exception of a few calciphilous species, forest trees are satisfied with moderate amounts of available calcium, such as 1,000 p.p.m., or 5 m.e. per 100 grams (Stone, 1940).

Calcium occurring in the exchangeable form is considered to be available to plants. Its determination is made by leaching the soil sample with a neutral salt solution, such as 1/N ammonium acetate, and by precipitating calcium as the oxalate (Chapman and Kelley, 1930).

Magnesium is a constituent of the chlorophyll molecule. It promotes the utilization of phosphorus and occurs most abundantly at the growing tips. Magnesium starvation may occur occasionally in nature and cause premature defoliation, preceded by chlorosis. In contrast to calcium deficiency, magnesium starvation does not affect the roots until later in the life of the plant. Magnesium salts in excess produce harmful effects, which may be lessened by the addition of calcium salts.

It has been suggested that plants require some definite calcium-magnesium ratio for their successful growth (Loew, 1920; Moser, 1933), but no concrete observations verifying such an assumption have thus far been reported in relation to tree growth.

The content of magnesium in forest soils is usually from one-fifth to one-third that of calcium (Wilde, 1938; Wilde and Patzer, 1940).

Exchangeable magnesium is determined by precipitation from the calcium filtrate by addition of ammonium phosphate (Chapman and Kelley, 1930).

Iron is essential to the formation of chlorophyll, and its deficiency is manifested by a yellowing of the leaves or "chlorosis". Iron is widely distributed in nature and its deficiency occurs only in circumneutral or alkaline soils in which iron is rendered less soluble. Such deficiency may be expected most often in calcareous soils low in organic matter (Kliman, 1937). In sandy nursery soils with a depleted content of humus, iron may become unavailable due to a heavy application of soluble phosphate fertilizers.

A deficiency of iron may be corrected by application of soluble iron salts to soils, spraying of the foliage, or injection of iron citrate or iron tartarate into the trunks of the trees (Thomas and Haas, 1928; Bahrt and Hughes, 1937).

Sulfur is a constituent of proteins and plays an important part in the respiration of plants. It appears to favor the development of roots, as well as root nodules. Although soils receive through the annual fall in rain and snow 3 or more pounds of sulfur per acre, this element may be deficient because of its loss in drainage. According to several reports, the addition of sulfur increased the growth of forest seedlings in nurseries.

Minor Nutrient Elements: — Information pertinent to the effect of boron, zinc, manganese, copper, and other trace elements on trees has accumulated largely in work with orchard soils. Most trace elements appear to act as catalysts stimulating the synthesis of chlorophyll and carbohydrates. They exert a beneficial influence upon plants when present in the soil in minute or moderate quantities; at higher concentrations they become toxic.

Boron has been found essential to the growth of citrus and pecan trees. Its deficiency depressed the rate of growth, and led to distortion of leaves, degeneration of terminal growing points, brittleness of stems, and discoloration of roots. A deficiency of boron is usually confined to either calcareous or depleted soils. An excess of this element causes a browning of leaves and premature leaf fall of walnuts. A deficiency of zinc is correlated with the so-called "deficiency diseases" of orchard trees, such as "pecan rosette". Spraying of leaves and treatment of soil with zinc sulfate have in many instances corrected a pathological condition of apple, pear, cherry, plum, and citrus trees.

A deficiency of manganese results in premature leaf fall and degeneration of growing shoots in citrus plants. A form of chlorosis characterized by yellow areas located away from the veins has been noted in a number of species due to manganese deficiency. Manganese chlorosis of pin oak, both in the nursery and in plantations, has been reported on soils with a high content of calcium carbonate. Chlorotic conditions of deciduous fruit trees have been traced also to a deficiency of copper. Applications of copper sulfate to the soil or directly to the leaves have corrected the "die-back" of citrus trees and improved the growth of walnuts affected with "yellows" (WILLIS, 1939).

Information on the acute deficiency of trace elements in forest soils is far from complete. A number of trials, conducted in the past ten years in forest nurseries of the Lake States and Central States regions have given no indication of such deficiencies.

Availability and Balance of Nutrients: — The nutrients which occur in soil as unweathered minerals and organic remains represent the principal capital of soil fertility. From this, plants receive a periodic income of soluble or available nutrients as they are released through the action of chemical and biotic agents. The available fraction in the form of soluble salts or exchangeable ions constitutes in some instances only 1 per cent of the total content (nitrogen, potassium), while in other cases it may be as great as 10 per cent (phosphorus, calcium).

The available nutrients are not at all limited to the fraction dissolved in the soil water as was believed originally by some. If the soil solution is not sufficiently supplied with certain nutrient elements, plants may feed directly on soil particles and derive nutrients from the exchange material or minerals. The "solid phase feeding" is facilitated by the close contact of root hairs with the soil particles and by the excretion of carbonic acid; the latter may produce in the proximity of the root hairs an acidity of *p*H 4.0 and thus may be an active agent in liberating replaceable bases and dissolving calcium phosphate (TRUOG, 1928). Solid phase feeding is especially common to forest trees and the lesser forest vegetation.

It is only in the rare instances of purely siliceous or highly calcareous soils that a deficiency of nutrients is caused by their entire absence in the parent soil material. As a general rule, the lack of available plant food is the result of intensive cropping, such as occurs in nursery soils, or of adverse conditions that render nutrients unavailable. The latter may be biological, chemical, or physical in nature.

Microorganisms, especially bacteria, consume large amounts of soluble nitrogen which they incorporate in their cells, thus rendering it unavailable to plants. Similarly, microorganisms may temporarily eliminate or reduce the supply of other nutrients. A condition of such "biological fixation" is most likely to occur in soils of a neutral or near neutral reaction in which the activity of microorganisms is often very energetic (RUSSELL, 1936). On strongly acid soils, a deficiency of available nitrogen, particularly nitrates, results from retarded activity of certain bacteria. The absence of other specific microorganisms, especially mycorrhizal fungi (ROSENDAHL, 1942), may also be a reason for unavailability of certain nutrients.

Either a strong acidity or calcareous condition of soils is conducive to chemical fixation of available phosphates which are converted into difficultly soluble iron and calcium phosphates, respectively (PRIANISCHNIKOFF, 1923). A more complex set of factors is responsible for the conversion of available potash into insoluble secondary micas or some other unavailable

form (VOLK, 1934). A high content of lime or alkali salts tends to render less available iron, boron, manganese, and probably other nutrient elements. Frequently certain ions minimize or offset the effect of other ions because of their so-called "antagonistic" behavior (STOKLASA, 1926).

Organic matter when applied to a soil at an insufficient depth, or as a top dressing, may arrest the downward growth of tree roots, and thus deprive seedlings of nutrients present at a greater soil depth (WILDE and WITTENKAMP, 1939). Inadequate aeration may be responsible for the conversion of nitrates into nitrites and, further, into elemental nitrogen. A number of other difficulties in the availability of nutrients may arise in the absence of proper oxidation. In fertilized soils of forest nurseries, a deficiency of buffering colloids causes disturbances in the absorption of nutrients due to "anastatic" or rapidly changing concentration of soil solution (GOLA, 1910).

The factors which render certain nutrients unavailable may bring about either starvation of forest stands or may disrupt the proper ratio of nutrients and lead to unbalanced growth of trees. The latter condition is much more common and important in artificially managed soils of nurseries than in natural stands.

Soil productivity is comparable to a power-utilizing machine. The presence of all growth constituents in reasonable amounts is just as necessary for satisfactory plant production as the presence of the smallest screw or spring is essential for the efficient operation of a motor (MITSCHERLICH, 1909; LUNDEGARDH, 1931). This fact is all too often overlooked in the management of nursery soils; in many instances, the lack, or low availability, of a certain nutrient element leads to a waste of fertilizers containing other elements and results in the production of inferior planting stock.

Because the solution, absorption, and assimilation of nutrients by plants obey the law of mass action and chemical equilibrium, it follows that an excess of any element or compound in the soil may interfere with the metabolism of plants and lead to their abnormal development. The abnormal growth and subsequent deterioration of trees on soils with an unreasonably high content of soluble nitrogen provides a most striking illustration of such a condition. In general, experience indicates that nursery soils with a low level of fertility, but a balanced ratio of nutrients produce better planting stock than soils treated with heavy but one-sided applications of fertilizers. Recently, TURNER and HENRY (1939), reported highly instructive observations of the effects of the nitrogen-potassium balance upon the production and quality of several crops in hydroponics. Diagram 15 illustrates the ratio of both nutrients needed to produce optimum growth of roses at different times of the year. Similar relationships undoubtedly hold true in regard to the balance of other nutrient elements.

It may be accepted axiomatically that nutrients exist in a balanced state in soils of all productive forest stands. This balance is sustained by the combind effects of microorganisms and buffering colloids. Within certain limits, balanced nutrition is facilitated by the ability of trees to absorb nutrient ingredients selectively.

Because the microbiological processes and gradual release of nutrients through humification and exchange reactions cannot easily be duplicated

under pot-culture conditions, the analysis of virgin soils appears to furnish, at the present time, the best information regarding a balanced state of nutrients and associated fertility factors. The ideas expressed by HILGARD (1906) attain particular significance in forestry since the maximum production of dry matter, considered as an index of the optimum supply of nutrients for common agricultural crops (MITSCHERLICH, 1924), is not a dependable criterion in the production of well-balanced and hardy forest nursery stock.

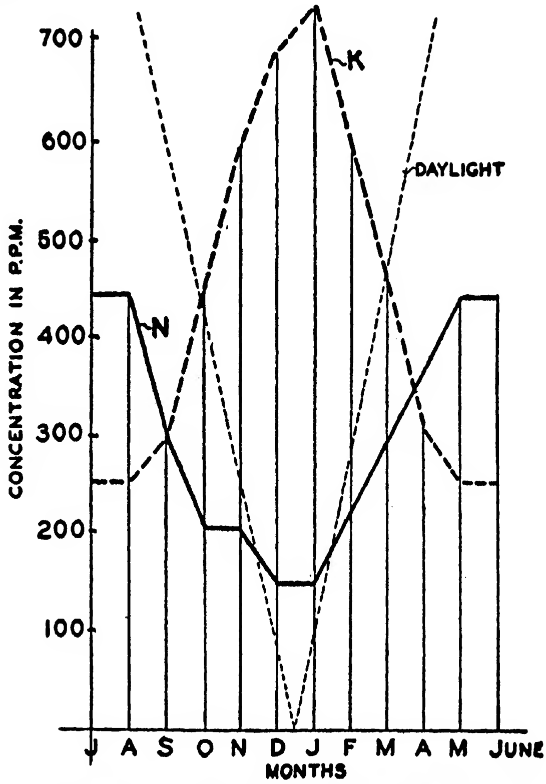


FIGURE 15. — Concentration of nitrogen and potassium in nutrient solution needed to produce optimum growth of roses at different times of the year; the dotted line represents the variation in daylight hours from the theoretical maximum of 15 hours in July to the minimum of 9 hours in December. (*Adapted by permission from* "Growing Plants in Nutrient Solutions" by TURNER and HENRY, published by John Wiley and Sons, Inc.).

Effect of Nutrition on the Morphological, Anatomical and Physiological Development of Trees: — The balance of nutrients is usually reflected in the balanced state of external and internal features of trees. In the evaluation of trees from the standpoint of their general development, their hardiness, and their suitability for planting or utilization, three types of balance should be given consideration: morphological, anatomical, and physiological. Each of these has specific silvicultural importance.

(1) *Morphological balance:* — In the early days of forestry practice, the quality of planting stock was judged by the size and color of foliage. In the course of time, it

was realized that the survival of trees in the field depends greatly upon the relative development of seedling roots, tops, and stems. At present, the root-top ratio and the relative stem diameters are the basic criteria in the evaluation of nursery seedlings. Because the development of trees is directly related to the content and the proportion of soil nutrients, especially nitrogen, potash, and phosphorus, the morphological balance of seedlings in forest nurseries is regulated through the addition of fertilizers. To some extent, the balanced development of seedlings is influenced also by the manner and the depth of fertilizer application (WAHLENBERG, 1929).

(2) *Anatomical balance:* — The anatomical balance is expressed by the relative development of plant tissues, size of cells, and thickness of cell walls. A balanced internal structure is of prime importance in the utilization of wood. Anatomical balance also plays a part in the resistance of trees to drought, wind, snow, and other adverse influences of environment.

Nutrients exert a profound influence upon the anatomical structure of plants. A complete or a partial starvation is manifested by a degeneration of the pith. Too rapid growth, caused usually by a high content of nitrogen, leads to thinning of cell walls. A deficiency of phosphorus and some other elements results in under-developed nuclei in the parenchymatic cells. In fact, any discrepancy in the nutritional balance tends to produce some anatomical abnormalities which decrease the general vigor of trees.

(3) *Physiological balance:* — Physiological balance is related to the chemical and colloidal composition of plants which determine the rate of plant growth, resistance of plants to unfavorable effects of climatic factors, and resistance to diseases. The entire process of nutrient absorption, or the "feeding power," is closely related to equilibrium conditions inside the plants (TRUOG, 1928). An unbalanced condition, leading in time to a deficiency of some nutrient elements, disrupts the normal synthesis of cytoplasmic compounds. As a result, unutilized salts may accumulate in large amounts and plasmolyze certain tissues. A shortage of potassium retards the conversion of starch into sugar and thus decreases the resistance of trees to frost. Numerous other physiological functions may be affected by internal chemical equilibrium conditions of plant tissues (MAXIMOV, 1938; MILLER, 1938).

The composition of plant tissues reflects to a considerable degree the supply of available soil nutrients. Therefore, the analysis of the entire seedlings or the foliage of trees may indicate the deficiency of certain nutrient elements or their unbalanced proportion (NEUBAUER and SCHNEIDER, 1923; THOMAS, 1937; MITCHELL, 1939).

Figure 16 illustrates the effect of nutrients upon the growth of forest tree seedlings.

Toxic Agents: — The productivity of a soil may be limited not only by a deficiency of nutrients, but also by the presence of certain ions or compounds in toxic concentrations. The toxicity of a soil is manifested either by an immediate injury of plants, or by their gradual deterioration. Soil toxicity is most dangerous during the initial period of tree growth (BRENCHLEY, 1927; TRUOG and SYKORA, 1917).

Under natural forest conditions, soil toxicity is of rather rare occurrence. A toxic concentration of the soil solution is sometimes met with in prairie-forest regions, particularly in depressions receiving run-off water. Soils derived from calcareous rocks in many cases contain carbonates of calcium and magnesium in sufficient amounts to be detrimental to trees, especially to acidophilous conifers. Hydrogen sulfide, accumulating in poorly drained soils, is toxic and may exert a depressing effect on the growth of trees. A high content of ferrous iron in the gley layer is believed to be harmful to vegetation (KOPECKÝ, 1928). High concentrations of soluble aluminum and manganese in the accumulative layers of podzol soils

appear to arrest the downward penetration of roots (MAŘAN, 1938). Most of these adverse conditions, however, play only an indirect and not necessarily significant part in the growth of natural forest stands.

The effect of toxic agents is, however, often important in soils of permanent forest nurseries. An injuriously high content of salts frequently

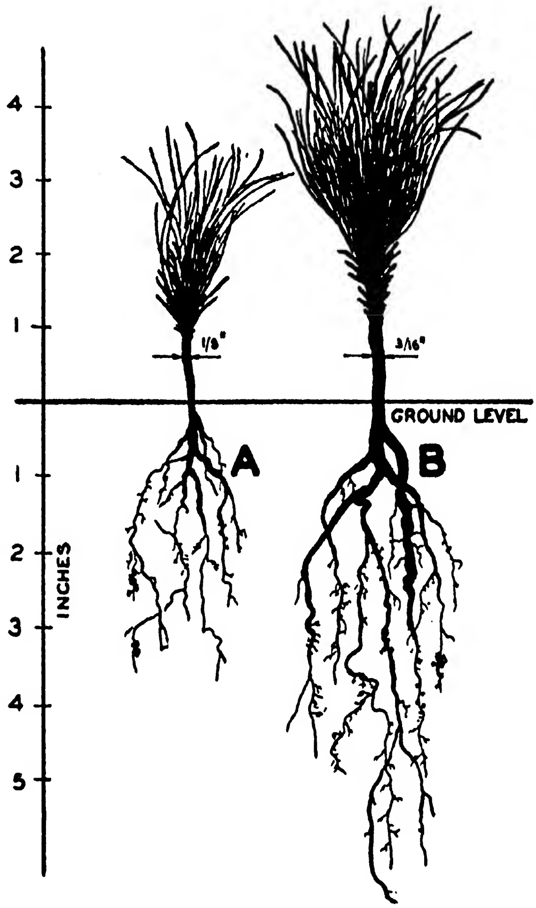


FIGURE 16. Growth of a 2-year-old red pine on a depleted nursery soil (A) and a similar soil treated with fertilizers (B) (*Silhouettes from a photograph*).

accumulates, as a result of evaporation, in the surface layer of sandy nursery soils treated with heavy applications of fertilizers. In some instances, a high calcium content and high temperature bring about an abnormally rapid rate of biological processes leading to an accumulation of soluble salts in toxic concentrations. Nursery soils treated with animal manures or sludge fertilizers are especially subject to this type of injury. The injury by an excess of salts is manifested by "burning" of the roots which become shriveled and black in color. Depending on the

degree of damage, the seedlings may either wilt or produce secondary roots and recover. A similar type of injury is encountered following treatments with sulfuric and other acids (HARTLEY, 1921). In nurseries using "hard" water, soluble bicarbonates may be brought to the soil surface by evaporation and form a carbonate crust. Such a condition may lead to destruction of the entire seeding.

Several cases of injury of nursery stock by sodium salts have been reported from nurseries in the prairie and Rocky Mountain states. A continuous application of nitrate of soda may lead to an accumulation of toxic quantities of sodium in the exchange material after the nitrate ion has been absorbed by the plants. The potassium carbonate present in wood ashes where brush was burned is often the cause of barren spots in recently cleared nurseries or on cut-over lands. Fresh sawdust applied in large quantity exerts a strong depressing influence upon the growth of young seedlings (VILJOEN and FRED, 1924); this effect is caused chiefly by the high carbon-nitrogen ratio and partly by the presence of toxic substances, such as oils and resins. The application of nitrate fertilizer may alleviate this condition to some extent.

A toxicity of soil in various degrees may result from the application of fungicides and insecticides. Aluminum sulfate used in large quantities for acidification of soils and control of damping-off fungi may depress the growth of seedlings and bring about a gradual deterioration of stock. The toxic effect of aluminum ions is most pronounced in non-calcareous sandy soils, where injury may be caused by a concentration as low as 200 p.p.m. of aluminum sulfate salt. The toxic intermediate products of sulfur oxidation may destroy germinating plants if sulfur is applied shortly before seeding. On sandy soils of *p*H 6.0, an application of 300 pounds per acre of sulfur powder at the time of seeding proved to be decidedly toxic. Lead arsenate, applied to nursery soils for the poisoning of white grubs, has caused numerous injuries to nursery stock. This toxicity is due to both the lead and arsenate ions. A burning of the roots and a reddening of the leaves are the symptoms of injury. Injured seedlings usually remain in depressed condition and must be culled. On poorly buffered and acid soils, a content of lead arsenate higher than 100 p.p.m. is detrimental. Injury from creosote is a rather common result in nurseries using impregnated boards for bed construction. The injury is usually confined to a narrow strip of seedlings adjacent to the frames. The losses of oil and grease from nursery equipment or dispersion of oil used in road treatments are sometimes responsible for deterioration of nursery stock and roadside plantations. Discarded waste, such as garbage, cinders, soap water, and cleaning solutions cause decadence of trees around dwellings. Concentration of animals on small areas such as found in mink farms, may also lead to deterioration of trees.

The following common remedies are used in counteracting soil toxicity: plowing, rototilling, scraping off surface soil, tile drainage, artificial irrigation, raising and removal of field crops, green manuring, application of acid peat, peat high in bases, raw humus, liquid humates, lime, wood ashes, various fertilizers, especially nitrates, ammonium sulfate, ammonium phos-

phates, and low grade superphosphates, use of sprays containing iron, and injections of iron citrate.

Base Exchange Properties of Forest Soils: — When a soil sample is leached with an aqueous solution of ammonium sulfate, the analysis of the leachate will show some removal of ammonium and an equivalent gain in the content of calcium, magnesium and other cations. This is because the base exchange material of the colloidal fraction of the soil has exchanged some of its cations for ammonium ions of the solution. An exact analysis of the leachate after such an exchange reaction will show that the solution has preserved its original cationic concentration and hence the loss of absorbed ammonium was compensated for by the release of an equivalent amount of other cations. This process may be illustrated by the following type equations in which X represents a portion of the large anion of base exchange material:

$$(NH_4)_2SO_4+CaX \rightarrow (NH_4)_2X+CaSO_4, \text{ or}$$
$$(NH_4)_2SO_4+K_2X \rightarrow (NH_4)_2X+K_2SO_4$$

The same type of reaction will take place if a solution of some other salt is used in the treatment of the soil instead of ammonium sulfate. Thus, fertilizing a soil with a solution of sodium nitrate will produce, among other reactions the following:

$$2NaNO_3+K_2X \rightarrow Na_2X+2KNO_3, \text{ or}$$
$$2NaNO_3+CaX \rightarrow Na_2X+Ca(NO_3)_2$$

The salts in solution replace from acid soils not only bases but also hydrogen:

$$2KCl+H_2X \rightarrow K_2X+2HCl$$

As a result of ionic exchange, an application of fertilizers leads commonly to the absorption of the positively charged cations with the release of other bases or hydrogen into the soil solution. The released cations combine with the free anions of acid radicals in solution to form acids and salts of varying solubility. The acids and easily soluble salts, such as HCl, H_2SO_4, H_2CO_3, KCl, Na_2CO_3 and $CaCl_2$ may be leached from the soil by percolating water. The difficultly soluble compounds, *i.e.,* $CaCO_3$, $MgCO_3$, and CaX remain in the soil.

The conversion of a soluble phosphate salt to the insoluble tricalcium phosphate is an outstanding example of fixation:

$$CaH_4(PO_4)_2+2CaX \rightarrow 2H_2X+Ca_3(PO_4)_2$$

The understanding of exchange reactions, only arrived at during the past several decades, has revolutionized the whole concept of plant feeding and has placed fertilizer practice upon a firm scientific foundation (Way, 1850; Gedroiz, 1918; Hissink, 1922; Truog, 1938).

The colloidal fraction of soils, capable of retaining and exchanging cations, including hydrogen, is termed the "base exchange complex", "ion exchange compound", or simply "exchange material." This exchange material exists in two forms, namely, mineral and organic. The mineral or

"zeolitic" fraction consists of aluminum or iron silicate clay minerals, whereas the organic or "humate" fraction is a lignin-like humus compound. In spite of their entirely different composition, both materials show a great similarity in many respects. Their chemical structure is based upon tetravalent elements, silica and carbon. The mineral exchange material consists of microscopic and ultra-microscopic crystals, which have a porous structure allowing the penetration of water and ions as do the organic colloids. With respect to the retention of nutrients both fractions act inseparably in the soil and their common effect is measured in terms of "base exchange capacity."

The relative proportion of various ions absorbed by the soil exchange compounds depends partly upon the "energy of absorption" of these ions and partly upon their concentration in the solution.

The energy absorption or "replacing power" usually increases with valence and atomic weight. Thus, the Ba-ion is more readily absorbed by the soil than the Ca, Mg, K, or Na ions, the latter having the lowest energy of absorption. However, hydrogen is an exception. Thus, the replacing power of the most important ions is given in the following order of diminishing activity:

$$H^{+}\ Ba^{++}\ Ca^{++} Mg^{++}\ K^{+}\ NH_4^{+}\ Na^{+}$$

The energy of absorption is not necessarily a criterion of the stability of the ions in the exchange compound. While H-ion is absorbed and also held more energetically than others, the less readily absorbed ions of the alkaline earth metals are the least readily displaced by the other ions.

These relationships are subject to modifications effected by the relative concentration of ions present in the soil solution, the exchange reactions being governed by the principle of mass action. According to this principle, any ion absorbed by the exchange material may be replaced by another ion occurring in the soil solution in considerable excess. Consequently, all of the bases and hydrogen may be replaced by ammonia if the soil is repeatedly leached with a solution of ammonium sulfate or ammonium acetate. The absorbed ammonia may be replaced by calcium by a similar treatment with calcium chloride. After the compound is completely saturated with the Ca-ion, this ion may be in turn removed and the colloids resaturated with the NH_4-ion by treatment with ammonium acetate. Base exchange reactions have been responsible for many relationships incomprehensible to early investigators.

Silvicultural Importance of Base Exchange Material: — Under natural conditions, the exchange compounds of soils are saturated predominantly with hydrogen and calcium, occurring in various proportions. The application of fertilizers, however, may greatly change the natural ratio and saturate the soil colloids largely with other ions such as those of ammonium, potassium or sodium. Soils having the exchange material saturated with bases have a neutral or alkaline reaction and are referred to as "base saturated" soils. The soils in which the exchange compound is, to a great extent, saturated with hydrogen are of acid reaction and are known as "base unsaturated" soils. The latter condition is more common in forest soils.

The high capacity of exchange material for holding water, and the marked influence of absorbed bases on the coagulation of colloids and the development of soil structure enables the exchange material to exert a profound influence upon the physical properties of soils.

In connection with plant nutrition, the exchange material acts as a storehouse in which bases are preserved in a form available to plants and yet

not easily removable by water. The carbonic acid, excreted by the root hairs, exchanges its hydrogen for ammonia, potassium and other bases of the exchange compound. These enter the soil solution and form, with liberated acid radicals, the soluble bicarbonates which are utilized by the root systems.

The base exchange capacity of soils detefmines the rate at which fertilizer may be safely applied to nursery soils. On heavy textured soils, rich in organic matter, and having an exchange capacity of about 15 m.e. per 100 g., as high an application as 1,200 pounds of total salts per acre may be a safe and economical practice, since most of the nutrient cations will be absorbed and preserved from leaching by the base exchange material. In dealing with the sandy soils, especially those poor in humus, and with a capacity not exceeding 5 m.e. per 100 g., a direct heavy application of fertilizers would be very uneconomical as most of the applied nutrients would be leached out before the seedlings could utilize them. Hence, on such soils, the applied fertilizers must be incorporated in composts or in the tissues of catch crops, or added to the soil in small portions as liquid fertilizers distributed over the whole period of stock development (Wilde and Kopitke, 1940). In order to attain a greater freedom in fertilizer practice, the general tendency in dealing with sandy nursery soils is to increase the soil exchange capacity to an approximate level of 10 m.e. per 100 grams by the application of clay, peat, or other suitable materials.

Table 10.—*Exchange Capacity of Representative Genetical Types of Virgin Forest Soils:*—

Weakly Podzolized Sand		Podzol Loam		Nut-Structured Grood Loam		Gley Loam	
Horizon	m.e./100 g.	Horizon	m.e./100 g.	Horizon	m.e./100 g.	Horizon	m.e./100 g.
A_0	13.7	A_{00}	76.3	A_{00}	87.3	A_0	65.5
A_1	7.8	A_0	83.2	A_1	21.5	A_1	32.2
A_1	5.7	A_2	4.3	A_2	6.72	A_2	6.7
A_2B	2.1	B_1	7.4	A_2B	11.04	B	11.7
A_2B	1.9	B_1	15.6	B_1	17.57	BG	8.3
C_1	0.4	B_2	15.9	B_2	13.66	G_1	6.1
C_2	0.5	C	12.1	C	7.06	G_2	5.4

Because of the strong tendency of the exchange material to react with the dissociated cations of the soil solution, some harmful constituents may be eliminated from the soil by introduction of desirable ones. In this way, nursery soil may be freed of toxic Na-ions, accumulated from repeated applications of sodium nitrate, by introduction of potassium chloride fertilizer. The treatment of nursery soils with sulfur is essentially a similar process in which the hydrogen ions of the sulfuric acid free the soil of an excess of calcium.

A knowledge of the exchange capacity values which include the total effect of both mineral and organic colloids, *i.e.*, clay and humus, is useful not only in fertilizer practice, but in the entire technique of forest soil utilization, especially in the selection of species for planting. The exchange capacity for the whole soil profile is of particular significance since it reflects

the physical, chemical, and genetic nature of the soil. Table 10 presents the exchange capacity values of several typical soil profiles from the state of Wisconsin.

Determination of Base Exchange Capacity: — The base exchange capacity of soils is commonly determined by a slow leaching of the soil sample with a normal solution of calcium chloride adjusted to *p*H 7. After washing out the excess of chlorides with distilled water, the absorbed calcium is removed by leaching with a normal solution of ammonium acetate and determined by precipitation with sodium oxalate (Chapman and Kelley, 1930). The results are, as a rule, expressed in terms of milliequivalents. Such presentation places the absorbing capacity of soils on an equal basis in regard to all cations, and thus eliminates the complications arising from the differences in atomic weights and valences. For example, the atomic weight of calcium is 40 and its valence is 2; therefore one milliequivalent of calcium is equal to $(40 \div 2)$ 0.001 or 0.020 g. of calcium. If a soil has a base exchange capacity of 5 m.e. per 100 grams, it can ab-

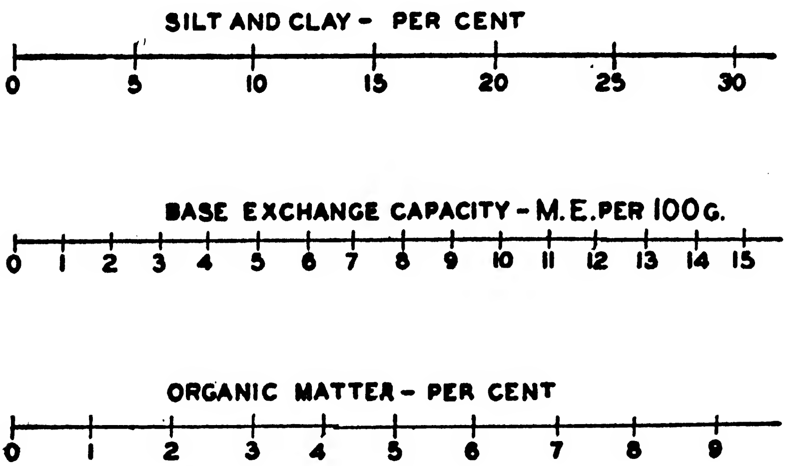


Figure 17. — Scale for approximate estimation of the base exchange capacity of sandy forest nursery soils on the basis of their contents of silt and clay and organic matter as determined by rapid tests.

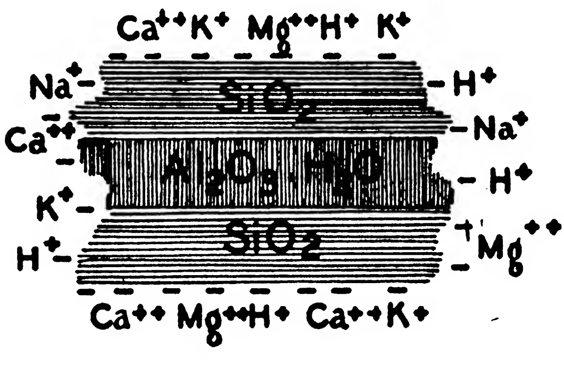
A straight line connecting the percentages of silt and clay particles and of organic matter passes through the proper value of the base exchange capacity. For example, a soil having 15 per cent of silt and clay and 2 per cent of organic matter has an approximate base exchange capacity of 5.3 M.E. per 100 grams of soil.

sorb or hold in replaceable form $5 \times .02$ or 0.1 gram of calcium per 100 grams, or 0.1 per cent. Since the weight of the surface soil layer (7″ layer) of an acre area is about 2,000,000 pounds, the amount of absorbed calcium will be 2,000 pounds per acre. According to similar calculations, the same soil would absorb 1,200 pounds of magnesium, and 3,900 pounds of potassium per acre.

Notwithstanding the great importance of the base exchange capacity of soils, the laborious analytical procedure involved in its determination has in the past limited its use as a criterion in practical nursery soil management. Fortunately, base exchange capacity is quantitatively related to the content of mineral and organic colloids. Because of this, in routine analyses of nursery soils, a fairly close approximation of the exchange capacity can be attained by the rapid determination of the contents of the fine soil material and organic matter. In outwash sandy soils derived from granitic rocks, for instance, each per cent of the fine soil material corresponds to about 0.25 m.e. of exchange capacity per 100 grams of soil. Similarly, each per cent of organic matter corresponds to about 0.8 m.e. per 100 grams. A diagram constructed on the basis of

these data permits a rapid estimation of the base exchange capacity (Figure 17). If the exchange values for mineral and organic fractions are established on the basis of a sufficient number of determinations for soils of the same geological origin and a fairly narrow textural range, a degree of accuracy entirely adequate for practical purposes can be obtained by this indirect method.

The detailed information pertinent to chemical analysis of soil and determination of forest soil fertility is treated by GEDROIZ, 1926; A. O. A. C., 1930; WILEY, 1931; WRIGHT, 1934; THORNTON *et al.*, 1934; TRUOG, 1937; WILDE, 1938, and MORGAN, 1941.



Chapter VIII

ORGANISMS OF FOREST SOILS

Role of Organisms in Soil Development and Forest Growth: — The soils of forests harbor multitudes of organisms living in burrows, in contact with colloidal material, and in the soil solution. Numbers of organisms per gram of soil range from several hundred thousands in sands to many millions in rich mull loams. Their total dry weight in one acre of forest soil is often as high as several tons (WAKSMAN and STARKEY, 1931).

The soil organisms exert a profound influence upon both the genetical development of the soil profile (MALCHEVSKAIA, 1933) and the growth of forest vegetation (BORNEBUSCH, 1930; FEHER, 1933). Nearly all members of the soil population are employed in the decomposition of organic remains. Organisms increase the availability of plant food through oxidation, evolution of carbon dioxide, and symbiotic action, or render nutrients unavailable through their reduction and incorporation into the protoplasm. The fixation of atmospheric nitrogen and carbon is primarily a biological process. Both metabolism and absorption of salts by organisms aid greatly the retention of plant food in the upper soil layers. The organisms modify the mobility of soil colloids and affect the formation of soil aggregates. Some forms hasten the germination and distribution of seeds, while others destroy the seed, root systems and other plant tissues (STOKLASA and DOERELL, 1926; OMELIANSKY, 1931; WAKSMAN, 1932; RUSSELL, 1936).

The entire soil population, or "edaphon" (FRANCÉ, 1921), includes bacteria, fungi, actinomycetes, algae, protozoa, nematodes, worms, insects, rodents, moles, shrews, and other soil-inhabiting animals.

Determination of Numbers of Soil Organisms: — The number of microorganisms is determined by making a series of dilutions of a suspension of soil, humus, or compost. A definite amount of suspension from each dilution is transferred to petri dishes and nutrient agar is added. After incubation, colonies of bacteria and fungi are counted and the number of microorganisms is calculated per gram of soil or other material (FRED and WAKSMAN, 1928). For the determination of soil fauna, the sample of soil or humus is placed in a modified Berlese funnel on a copper screen and the animals are forced by an electric light or other means into a beaker containing a mixture of alcohol, glycerine, and dilute acetic acid. The contents of the beaker are transferred into a petri dish and counts are made with low power microscope (EATON and CHANDLER, 1942).

Bacteria: — The bacterial population of soil falls into two broad groups determined by the mode of nutrition:

(1) *Autotrophic bacteria* which live wholly or partially without organic matter, utilizing elements or simple compounds for energy and deriving body carbon from carbon dioxide. To this group belong nitrite and nitrate-forming bacteria and bacteria oxidizing sulfur, iron, hydrogen, or carbon monoxide, methane and similar carbon compounds.

(2) *Heterotrophic bacteria* which do not assimilate carbon dioxide and feed chiefly on organic matter. To this group belong free and symbiotic nitrogen-fixing bacteria, bacteria decomposing fats, proteins, cellulose and

other carbohydrates, and some denitrifying bacteria. A considerable portion of heterotrophic forms live in the absence of oxygen and are called "anaerobic" in contrast to "aerobic" forms developing in the presence of air.

The outlined division is of a great practical importance in the management of forest soils, particularly forest nursery soils. Organic matter is essential in the maintenance of soil fertility. The normal nutrition of trees can seldom proceed without participation of soil bacteria. Some of these organisms live on organic residues, which they gradually destroy, while others not only prefer purely mineral substances but may even be injured by organic matter. Under natural conditions all of these seemingly paradoxical tendencies are in perfect correlation (WINOGRADSKY, 1938). However, unskilled application of organic matter and mineral fertilizers may easily destroy the existing equilibrium of bacteria and upset the nutrition of nursery stock. Therefore, the maintenance of the soil microorganisms in a state of natural balance is one of the important problems of modern silviculture. A discussion of the more important nutritional effects exerted by various groups of bacteria follows.

Protein-Decomposing and Ammonifying Bacteria: — The bulk of nitrogen in soil, forest litter and organic fertilizers is in the form of proteins. These cannot be utilized by trees directly and must first be broken down into simple compounds such as ammonia and nitrates. The process of decomposition is accomplished by combined action of chemical, enzymatic, and biological agents, particularly by aerobic and anaerobic bacteria (*Bacillus mycoides, Bac. subtilis, Bac. putrificus, Bact., vulgare,* etc.). In some instances, the chain of transformations is concluded by the formation of ammonia which is released as a waste product of ammonifying bacteria. Under aerobic conditions, however, ammonia may be further transformed into nitrates by nitrifying bacteria.

Nitrifying Bacteria: — The transformation of ammonia nitrogen into nitrates is accomplished by two groups of aerobic bacteria. Some of these oxidize ammonia to nitrites (*Nitrosomonas*), whereas others oxidize the nitrites into nitrates (*Nitrobacter*).

Good aeration, adequate supply of water, fairly high temperature, presence of buffers, and the absence of large quantities of soluble organic matter or highly concentrated salts are essential for the success of nitrification. As a rule, nitrification is promoted by a reaction approaching neutrality, although some organisms specifically adapted to acid media produce nitrates in forest soils having a reaction as low as *p*H 4.8 (HESSELMAN, 1916-17).

The maintenance of soil in a condition suitable for the propagation of nitrifying bacteria is important chiefly in dealing with deciduous, lime-loving tree species requiring nitrogen in the form of nitrates. On the other hand, certain deviations from the nitrification optimum may be tolerated in stands and nurseries with acidophilous and especially saprophytic conifers, as such species readily utilize the nitrogen of ammonia, and possibly amino-acids.

Determination of Nitrifying Capacity in Soil: — For the determination of nitrifying capacity about 50 g. of air-dry soil or an equivalent volume of pulverized organic remains are incubated in covered tumblers at a temperature of 28° C. after the moisture content of material is brought to two-thirds of saturation. A weekly determination of the nitrates by the phenoldisulphonic acid method gives a picture of the activity of nitrifying organisms. If the soil is low in organic matter, 0.1 g. of ammonium sulfate may be added to the sample before incubation (FRED and WAKSMAN, 1928).

Denitrifying Bacteria: — Under anaerobic conditions certain bacteria derive their oxygen supply from the oxides of nitrogen. In this process the nitrate is reduced to nitrite and further to elemental nitrogen with the simultaneous oxidation of other food substances by the microorganism involved. The group of bacteria capable of denitrification includes hundreds of species greatly diversified in their other activities.

The reduction of nitrates to nitrites usually takes place in wet soils of neutral or somewhat alkaline reaction. In acid soils nitrates are likely to be reduced to ammonia with nitrites as an intermediate product. The adverse effects of denitrification are largely limited to stands of lowland hardwoods and nursery stock on heavy soils.

Nitrogen-Fixing Bacteria: — Although an abundant supply of elemental nitrogen is always present in the atmosphere, it is not available to trees until it is converted into the form of simple compounds. A rather negligible portion of this conversion is accomplished by electrical discharges; the rest is brought about by the activity of nitrogen-fixing bacteria. Such bacteria occur in nature either as free organisms or in symbiosis with higher plants. The latter form nodules on plant roots and are commonly referred to as "nodule bacteria."

The free nitrogen-fixing organisms include aerobic and anaerobic forms. Aerobic forms (*Azotobacter*) are extremely sensitive to the acidity of soil and other conditions, and their distribution is confined chiefly to well-aerated loam soils with reaction above *p*H 6.0. Consequently, these bacteria are of secondary importance in the maintenance of forest soil fertility. The anaerobic forms (*Clostridium* or *Amylobacter*), occur nearly universally in soils with the possible exception of acid peat bogs, and play a part in the growth of both forest stands and nursery stock. A reaction not lower than *p*H 5.5, an adequate supply of organic matter and mineral plant food, and a fairly high temperature are essential for the optimum activity of these organisms (Němec and Kvapil, 1924).

In the symbiotic fixation of nitrogen, leguminous plants provide nodule bacteria with carbohydrates and in return receive nitrogen compounds. The nitrogen accumulated by nodule bacteria is likely to be directly available and is transferred to the plant at a rather constant rate.

The nodule bacteria (*Rhizobium*) are usually quite specific in their host requirements. They can withstand about the same *p*H as their respective hosts. The forms associated with soybeans, lupines, and some vetches can survive at *p*H 4.0, thus permitting their advantageous use in forest nurseries. In spite of the great tolerance of certain legume bacteria to acidity, the rate of nitrogen fixation is usually increased by the addition of lime. Mineral fertilizers and organic remains are also indirectly effective, due to increased growth of the host plant.

In the great majority of cases, inoculation of seeds or soil with the proper culture of bacteria is necessary to obtain satisfactory results with leguminous green manure crops. Some forest trees, such as black locust, are dependent in their nitrogen nutrition upon bacteria and may also require artificial inoculation. Although the bacteria are often present in nursery soils, their viability is greatly influenced by *p*H, organic matter, moisture, temperature, and toxic agents. Consequently, it is advisable to inoculate seed with a known effective culture rather than to depend upon the presence of the organism in the soil (Fred, Baldwin, and McCoy, 1932).

Carbohydrate-Decomposing Bacteria: — Carbohydrates comprise the greatest portion of organic matter. They include sugars, starches, cellulose, and hemicelluloses. Cellulose is the most abundant constituent, and the process of its decomposition has a particularly important bearing upon soil productivity.

The role of cellulose in plant nutrition is of a complex nature as it may exert either beneficial or harmful influences. Cellulose serves directly or indirectly as a source of energy for nitrogen fixing bacteria and other useful organisms, but has no value as a plant nutrient or base exchange material. In large quantities it encourages the growth of organisms utilizing ammonia and nitrates and thus may cause the nitrogen starvation of trees. For this reason, the productivity of soil, as well as the quality of composted fertilizers, may be greatly decreased by a high content of cellulose.

The bacteria concerned in the decomposition of cellulose include both aerobic and anaerobic forms (*Cellulomonas,* certain *Spirochaetes* and *Clostridia*). In compost piles with a high temperature, these organisms may be partly replaced by thermophilic bacteria (*Clostridium thermocellum*). The mechanism of cellulose decomposition varies depending upon the conditions of environment and the organisms involved. How-

ever, the end products usually include carbon dioxide, methane, hydrogen, other gases, and bacterial cells mixed with other decay-resistant substances.

The aerobic cellulose-decomposing bacteria are very intolerant of poor aeration and soil acidity. Their activity ceases completely at a reaction lower than *p*H 5.5. Consequently, they are confined chiefly to hardwood mull loams and weakly podzolized pine sands. The anaerobic bacteria withstand both strong acidity and deficiency of oxygen and occur abundantly not only in poorly drained and acid forest soils but also in deposits of peat and over-watered compost piles.

Raw organic remains applied in forest nurseries as fertilizing material usually contain about 40 per cent of carbon and 2 per cent of nitrogen. When such remains are added to a nursery soil, cellulose-decomposing bacteria multiply rapidly, using for their cells both carbon and nitrogen. As the bacterial cells are composed approximately of one part of nitrogen and five parts of carbon, the supply of nitrogen present in both soil and organic remains may be soon exhausted. Unless the soil receives a new supply of nitrogen in the form of fertilizers, its deficiency will arrest the process of decomposition and bring about the starvation of nursery stock. Such consumption of nitrogenous compounds by cellulose-decomposing bacteria often takes place during the preparation of composted fertilizers and may be prevented by applications of soluble nitrogen salts.

The decomposition of hemicelluloses and other carbohydrates is on the whole similar to that of cellulose, except that it proceeds more rapidly and plays a less important part in the state of soil fertility.

Sulfur Bacteria: — From the standpoint of nutrition, sulfur is closely related to nitrogen and undergoes similar biological transformations. The oxidation of elemental sulfur and sulfides into available sulfates or sulfuric acid is accomplished primarily by a specific group of sulfur bacteria (*Thiobacillus, Beggiatoa, Thiothrix*).

The accumulation of sulfuric acid is followed by an increase in soil acidity. Since the acidification of nursery soils supporting coniferous stock is often desired, the sulfur-oxidizing bacteria and their well-being attain a considerable importance in forestry practice. The activity of these forms is stimulated by additions of flowers of sulfur and various organic remains, *viz.*, green manure, peat, duff, or compost. The oxidation of sulfur is of further benefit in the preparation of composted fertilizers where the sulfuric acid formed converts the insoluble rock phosphates into available mono-calcium phosphate.

The reduction of sulfates or other sulfur oxides to hydrogen sulfide is similar in its nature to denitrification and may be accomplished by a wide variety of both autotrophic and heterotrophic organisms capable of carrying on anaerobic respiration. *Sporovibrio desulfuricans*, a strictly anaerobic Spirillum, plays an outstanding part in this transformation. The reduction of sulfates takes place prevailingly in poorly-drained soils, especially peat and muck. The accumulated hydrogen sulfide exerts a toxic effect upon the roots of the trees and may be partially responsible for poor growth of trees in stagnant swamps.

Iron Bacteria: — A number of bacterial forms (*Crenothrix, Leptothrix, Gallionella*) derive their energy from the oxidation of ferrous iron, thereby converting it into the difficultly-soluble ferric precipitate. This process may play a certain part in the development of iron-rich horizons of forest soils. Aside from the activity of the iron bacteria proper, a number of other bacteria may cause development of a hardpan or bog-ore by using the organic fraction of soluble iron humates and leaving iron hydroxide as a residue.

Fungi: — Fungi are multicellular chlorophyll-free thallose plants deriving their energy from decomposition of dead or living organic matter. They occur in soil either as free molds or as symbiotic fungi forming mycorrhizae on the roots of higher plants. Both of these groups include minute forms with microscopic filaments as well as the higher mushroom fungi.

Fungi tend to dominate raw organic remains of forest soils. At the same time, they are strongly influenced by the supply of mineral nutrients.

Many of the fungi can withstand high acidity and occur in great numbers in acid forest soils. The number of fungi increases with soil moisture content, provided there is adequate aeration. Although the greatest density of fungal population is found in the upper few inches, fungi occur in the soil profile to a depth of 4 or 5 feet. Fungi in greater or lesser quantity occur throughout the entire range of soil conditions suitable to forest growth. *Aspergillus, Botrytis, Fusarium, Monilia, Mucor, Oidium, Penicillium, Phytophthora, Pythium, Rhizoctonia, Rhizopus, Sclerotium, Trichoderma, Verticillium, Zygorhynchus, Armillaria, Amanita, Boletus, Cortinarius, Merulius, Phoma,* and *Russula* are among the most common genera found in soils. The role of fungi in forest soils cannot be over-emphasized. Fungi are largely responsible for the decomposition of proteins, cellulose and most of the other carbohydrates.

Under ordinary conditions, the activity of fungi proceeds very efficiently with comparatively little consumption of energy materials and results in the accumulation of a highly nitrogenous residue of fungal mycelia. The accumulation of large quantities of available nitrogen takes place because the fungi consume primarily the carbohydrate fraction of the protein compounds and release ammonia as a waste product. In some instances, however, fungi temporarily remove the soluble nitrogen compounds and other mineral nutrients as do bacteria. They release them only after the source of energy, *i.e.*, the carbohydrate fraction, is exhausted and the dead mycelia are decomposed. While the consumption of nitrogen may have a temporary depressing effect upon the seedlings, it preserves the soluble nitrate and ammonia compounds from leaching by rain or artificial watering.

Fungi may modify considerably the reaction of soil by the liberation or consumption of organic acids and by the formation of ammonia. In some instances they increase the availability of phosphates and other nutrients by evolving carbon dioxide. The conversion of difficultly-soluble compounds into available form by mycorrhizal fungi has an especial significance in the growth of trees and is discussed at length separately.

Some of the fungi do not draw an exact line between the dead and living organic matter and cause the destruction of tissue of seedlings and older trees. The so-called "damping-off" fungi, *Rhizoctonia, Pythium, Fusarium, Phytophthora,* and a few other genera, attack forest seedlings shortly after germination and are frequently responsible for great losses of nursery stock (Hartley, 1921; Boyce, 1938). In some instances damping-off fungi act as a factor limiting the distribution of certain species, particularly conifers (Wilde and White, 1939). In close relation to damping-off forms are root-rot fungi which cause the decay of the older seedlings and transplants. Among the fungi attacking the roots of older trees, black shoestring fungus, *Armillaria mellea,* and some members of the *Polyporaceae,* have the widest and the saddest reputation in both American and European forestry practice.

Mycorrhizae: — A great number of fungi exist in symbiosis with trees and other higher plants. The mycelium of such fungi enters the roots and causes certain modifications in the live tissues; the resulting new "fungus-root" organs are referred to as mycorrhizae (Frank, 1885).

The occurrence of mycorrhizae on roots of forest trees was first revealed by GASPARRINI (1856). Since then mycorrhizae have been detected and studied on the majority of forest trees, shrubs, and many ground cover plants by KAMIENSKY (1881), FRANK (1885), R. HARTIG (1886), MÜLLER (1886), SARAUW (1893), STAHL (1900), and many others. The most recent extensive investigations were made by MELIN (1925), in Sweden, and HATCH (1937), in the United States.

Depending upon the position of the fungus in relation to the cells of the host, mycorrhizae are classified as ectotrophic or endotrophic. In *ectotrophic mycorrhizae* the mycelium develops chiefly in the intercellular spaces and also forms a mantle on the surface of the roots. In *endotrophic mycorrhizae* the mycelium develops within the cells and only individual hyphae extend from the surface of the roots to the soil (FRANK, 1887). In either case, mycorrhizae connect the higher plants with a large volume of the soil through their extensive external mycelium. The spread of such mycelium is frequently indicated by "fairy rings" of mushrooms enclosing an area of many hundreds of square feet.

Ectotrophic mycorrhizae are formed on both conifers and hardwoods, especially on pine, spruce, fir, larch, hemlock, beech, oak, chestnut, hornbeam, and hazel-nut. Endotrophic mycorrhizae are associated with numerous other trees and vascular plants, but they are best known as symbionts of members of the *Ericaceae* and *Orchidaceae*.

Mycorrhizae of forest trees are formed chiefly by *Hymenomycetes,* such as *Boletus, Amanita, Tricholoma, Boletinus, Lactarius, Cortinarius,* and *Russula.* Some of the fungi, for example *Amanita,* may be associated with a wide variety of tree genera, whereas others, like *Boletus,* invade only a few tree species. In many instances, the relationship is very specific (ROMELL, 1939).

On soils having a high content of soluble salts or a reaction higher than *p*H 6.0, true mycorrhizae are said to be replaced by so-called "pseudo-mycorrhizae" produced by *Mucor, Verticillium,* and other common fungi (MELIN, 1925). In the writer's opinion, the replacement of true or beneficial mycorrhizae by non-beneficial pseudo-mycorrhizae under natural conditions must be a rare phenomenom. In work with a wide variety of nearly-neutral and alkaline forest soils, used as inocula, no such substitution was observed.

It is believed that the fungus derives carbohydrates from the root and in exchange supplies the tree with certain nutrients, particularly nitrogen (TUBEUF, 1903; FALCK, 1923; SÜCHTING, 1925). The nitrogen is supposed to be obtained by the fungus from soil organic matter; claims that mycorrhizae fungi fix atmospheric nitrogen have not been substantiated in spite of numerous efforts. The root may receive available nitrogen as a by-product of fungus metabolism, or may obtain it by digesting fungal hyphae. Since the formation of mycorrhizae often leads to the degeneration of root hairs, the entire intake of water and nutrients may be accomplished via the fungal mantle. The nutrition of trees thus may be essentially different from that common in field crops. Because of the high absorbing efficiency of fungus bodies and their great absorbing surface, mycorrhizae were believed to utilize difficultly soluble nutrients occurring in soil in the form of unweathered minerals (STAHL, 1900). Recently, it has been demonstrated that mycorrhizae actually increase the intake of potassium from feldspathic minerals (ROSENDAHL, 1942). Indirect evidence indicates that this is true of other nutrients, particularly phosphates and calcium (REXHAUSEN, 1920; MITCHELL, FINN, and ROSENDAHL, 1937). The effect of mycorrhizae in in-

creasing the availability of nutrients is of considerable practical importance; it may appreciably reduce the expenses for commercial fertilizers in nurseries and arboricultural plantations. The use of less soluble sources of potash and phosphates may prove to be not only cheaper, but also a safer means of fertility maintenance.

It was suggested as early as 1899 by WARD that "one symbiont may stimulate another by excreting some body which acts as an exciting drug to the latter". At present there is evidence that the fungus is dependent upon the higher plants for its supply of thiamin and other vitamins (HOW, 1940; ROSENDAHL, 1943). Future investigations may be expected to reveal that the fungus supplies tree roots with specific growth hormones (WHITE, 1941).

The abundance of mycorrhizal short roots, or ectotrophic mycorrhizae, is apparently correlated with a number of soil conditions, such as moisture content, reaction, base exchange capacity, nature of humus, and content or balance of nutrients. Mycorrhizae appear to be more numerous in soils of low general fertility or in soils deficient in some specific nutrient elements (CIESLAR, 1901; HATCH, 1937). The extent of mycorrhizal infection, therefore, is likely to be controlled by the concentration and balance of nutrients within the host plant.

A number of the earlier investigators (R. HARTIG, 1888; TUBEUF, 1888; MCDOUGALL, 1914) maintained that mycorrhizae are purely pathological developments. These views, however, have been superseded by many recent observations. Convincing evidence of the beneficial effect of mycorrhizae has been obtained by MELIN (1917) in his work with drained peat soils of Sweden. In such soils the seedlings lacking mycorrhizae showed symptoms of nitrogen starvation and eventually died, while seedlings infected with mycorrhizal fungi grew successfully. It has been also reported that seedbed inoculations saved a new nursery from abandonment in southern Rhodesia. Likewise, nursery failures in Australia have been traced to the lack of mycorrhizal fungi; satisfactory growth of seedlings was achieved by importation of soil infected with the proper organisms (CLEMENTS, 1938). In a forest nursery at Licking, Missouri, the growth of short leaf pine was found to be intimately dependent upon the infection of roots with fungi (MILLER, 1938). All successful plantations of introduced pines in the Philippines are known to have an abundant infection of mycorrhizae (OLIVEROS, 1932).

Especially spectacular results have been obtained in work with prairie soils of both Russia and the United States. As was long ago suggested by WISSOTZKY (1902), the establishment of trees from seed on prairie or chernozem soils has been found impossible without simultaneous inoculation of the soil with mycorrhizal organisms (HATCH, 1936; YOUNG, 1936; RAYNER, 1938; BARANEY, 1939). It appears that the entire problem of the persistence of treeless areas or "intrazonal prairies" in North America is connected with the absence of mycorrhizal fungi (WHITE, 1941). It is probable that mycorrhizae permit the growth of slow-feeding trees on prairie soils by more effective utilization of nutrients in competition with the abundant micro-population of such soils.

While mycorrhizae play a unique part in certain phases of silviculture, their general importance has often been grossly exaggerated. The claims that mycorrhizal fungi disappear from soils with the removal of trees and must be introduced artificially for direct re-seeding of old cut-over areas have not been confirmed. An examination of numerous samples taken throughout Wisconsin failed to show a single forest soil in which active mycorrhizae were absent. Even samples from partly forested sand dunes

or blowouts and cut-over areas more than 60 years old contained some mycorrhizal fungi (ROSENDAHL and WILDE, 1942).

Similarly, the assumption that mycorrhizal organisms are very particular in their environmental requirements and that their degeneration in unsuitable soils leads to the failure of planted trees has not been substantiated by observations.

Figure 18 and Plate 7 illustrate the effect of mycorrhizae on tree growth.

Actinomycetes: — Actinomycetes are generally classed as fungi although they exhibit characteristics of both fungi and bacteria. The body of these organisms consists of mycelia with branching non-septate hyphae

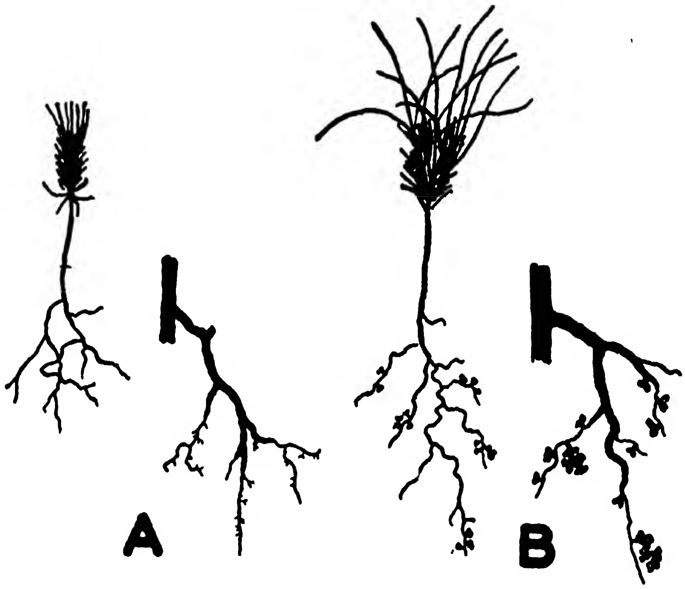


FIGURE 18. — Effect of mycorrhizae upon the development of one-year old red pine seedlings grown in prairie soil: A. Seedling grown without inoculation; B. Seedling grown from seed inoculated with a pure culture of *Boletus felleus*. (*Silhouettes from a photograph after* ROSENDAHL).

similar to those of higher fungi. The mycelium is brightly colored and is easily broken into short rods resembling bacteria. Most species produce a typical earthy odor of fresh soil. Actinomycetes occur primarily in forest soils where their main function is the decomposition of resistant lignin-like substances.

In contrast with fungi, actinomycetes are very sensitive to acidity, and disappear almost completely in soils having a reaction of *p*H 4.7 or lower. This may have a direct bearing upon the development of the highly ligneous duff layers of so-called "raw humus" forest soils. Some actinomycetes have the ability to reduce nitrates to nitrites and may be detrimental.

Algae: — Algae are chlorophyll-bearing organisms generally occurring in filaments or colonies. The algal flora of the soil is confined to three groups: *Cyanophyceae* or blue-green algae; *Chlorophyceae* or green algae, and *Bacillariaceae* or rod-shaped diatoms.

Algae hasten the solubility of minerals, particularly carbonates, and thus aid in processes of weathering. Being capable of photosynthesis, they utilize carbon dioxide and increase the content of soil organic matter. Lichens which are a symbiotic association of algae and fungi are of great importance in initiating plant succession and development of soil on unweathered rocks and other barren parent materials. It is possible that the growth of the higher plants, on poorly-drained soils is benefited by the oxygen given off by the algae.

Protozoa: — Protozoa are one-celled animals, varying in size from a few microns to several centimeters with protoplasms either naked or enclosed in a membrane and containing one or more nuclei. They participate in the decomposition of organic remains, and destroy certain parasitic, as well as useful organisms, particularly bacteria. In recent times, a theory has been advanced that protozoa materially decrease the fertility of agricultural soils, or even cause a so-called "soil sickness" by feeding on ammonia- and nitrate-forming bacteria (RUSSELL, 1936). Such a condition may be expected in over-watered heavy nursery soils high in organic matter, a medium favoring the multiplication of protozoa. Since protozoa are less resistant to heat than bacteria, a method of partial sterilization was advanced as a means of increasing soil fertility. However, this has not found an application in nursery practice.

Nematodes: — Nematodes are transparent, non-segmented, spindle-shaped, worm-like organisms. The soil-inhabiting forms are microscopic in size. They occur in great numbers in the humus horizons of forest soils and include parasitic, saprophytic and free-living species (*Tylenchus, Iota, Mononchus, Rhabditis,* and *Alaimus*).

Nematodes play an important role in the decomposition of organic matter and improve soil aeration. They consume bacteria, fungi, protozoa, and other nematodes and may be either injurious or beneficial depending upon the nature of destroyed organisms. By distributing parasitic fungi in nursery soil they may increase the extent of damping-off disease. Recent evidence from Wisconsin and New Zealand has shown that some of the nematode species (*Rhabditis*) invade the tissue of live coniferous seedlings, producing the same effect as damping-off disease, or at least completing the destructive work of fungi (HANSSON, 1936; WILDE, 1936).

Earthworms: — The worms inhabiting soil include chiefly the members of two families: *Oligochaeta-Terricolae,* having segmented bodies with four rows of bristles, and *Oligochaeta-Limicolae,* characterized by whitish color and the presence of more than two straight bristles in some of the bundles. *Lumbricus, Allolobophora, Octolasium, Eisenia, Helodrillus, Enchytraeus, Fredericia,* and *Anachaeta* are the most important genera.

With very few exceptions, the occurrence of earthworms is confined to moist soils rich in organic matter and of moderately acid or alkaline reaction. Loam and silt loam soils, high in bases and supporting hardwood stands, often have an especially abundant earthworm population and are sometimes referred to as "earthworm mull soils."

Earthworms drag fallen leaves into their burrows and use them either as litter or food, thus preventing the accumulation of duff. In the process

of nutrition they pass great quantities of soil and organic remains through their bodies, thereby promoting humification and the incorporation of humus with mineral soil. As a result, the upper layer of soil attains a typical crumby structure which increases aeration, diminishes runoff, and to some extent facilitates the root penetration of germinating plants (RAMANN, 1911; EATON and CHANDLER, 1942).

Undoubtedly the activity of earthworms has considerable beneficial influence upon the productivity of soils, as was originally stressed by DARWIN (1881). However, the presence of earthworms in forest soil is not always an indication of high soil productivity. Very often the abundant population of earthworms is found in soils with a high ground water level, where the trees stagnate due to deficient aeration of the deeper soil layers.

Arachnida: — Soil-inhabiting arachnida include mites, ticks and spiders. They are, as a rule, confined to the upper one-inch layer. In well-humified mull soils the total number of arachnida may reach several hundred thousands per acre. Being primarily carnivorous, arachnida play a certain role in the maintenance of biological equilibrium of the soil population and to some extent contribute to the processes of humification. Recently claims were made that mites are responsible for the injury of young seedlings (HANSSON, 1936).

Insects: — A great majority of insects spend a certain portion of their life cycle in the soil, and the total insect population of forest soils per acre may be estimated in terms of millions (STARK, 1930). Some of the insects feed on root systems (*Melolontha*) or on soil organisms (*Carabideae*), while others live saprophytically (*Collembola*) or simply use soil as a shelter (*Formicidae*). Finally, some insects occur in soil only in the pupal stage (*Lepidoptera*).

The insects benefit forest soils by addition of organic matter, humification and improvement of soil structure (ROMELL, 1935). Among the injurious insects, the white grub, wireworms, cutworms and root borers are of greatest importance (METCALF and FLINT, 1939). The first two destroy the roots of seedlings and transplants, whereas the latter cut the stems of young plants near the ground and feed upon the exuding sap.

In tropical forests termites act as a particularly outstanding soil factor by decomposing vast amounts of dead and living plants and by greatly increasing the soil porosity with their numerous passages.

Mammals: — Most of the larger animals that inhabit forest soils are moles and rodents. The passages of moles and shrews, and burrows of mice, chipmunks, woodchucks, and ground squirrels are among the characteristic features of some types of forest soils. The burrowing creatures depend in the choice of their habitat not only upon the supply of food, but also upon the physical conditions of the soil. For this reason, the distribution of these animals shows a rather close correlation with the soil types. For example, woodchucks are known to attain greatest density on gravelly sandy loams of glacial deposits. The chipmunk is one of the few inhabitants of strongly podzolized soils. Snowshoe rabbits show definite preference for alluvium and swamp-border soils. The mole is supposed to serve as a reliable indicator of productive humus-incorporated soils with abundant

edaphon, *i.e.,* "mull soils"; according to some foresters, the names *mull* and *mole* are of the same origin. The profiles of prairie-forest soils are often marked by abandoned passageways and nests of gophers, ground squirrels, and blind mole rats. Filled passageway of prairie animals, or "krotovinas" were used by DOKUCHAEV (1879) as a criterion for the establishment of relic prairies.

Burrowing animals contribute to the processes of humification, and in a measure supplement or replace the work of earthworms. Under unbalanced biological conditions, *i.e.,* in the regions where weasels and other predators are absent, mice, rabbits, and other rodents become highly destructive to the forest by devouring both seed and bark of the trees.

Chapter IX

FOREST HUMUS

Classification of Forest Humus: — The term *forest humus,* in its broad sense, refers to the entire organic portion of the soil profile (Waksman, 1938). It includes undecomposed leaves, needles and twigs, or *litter,* partly decomposed remains, or *duff,* and the finely-divided, decay-resistant residue, or *amorphous humus.* In many instances, the amorphous humus is mixed with the mineral soil partly by the action of organisms and partly through infiltration; it is then called *incorporated humus.*

Forest humus is a factor of extensive ecological significance and an important agent in the processes of soil development. The leaching of podzols, maintenance of the equilibrium of soluble salts in the melanized soils, and accumulation of sesquioxides in laterites are intimately related to the nature of humus. Different forms of humus modify the course of natural reproduction of forest stands and thus influence the technique of silvicultural cuttings. Forest humus is a seat of useful organisms, a source of nutrients, growth substances and buffering colloids; it plays a leading part in the maintenance of soil fertility in both forest stands and forest nurseries (König *et al.,* 1927; Sigmond, 1930; Bujakowsky, 1930; Morgan and Lunt, 1931; Wilde, 1937*a*; Heiberg, 1941).

The first classification of the organic layers of forest soils is accredited to the German forester Emeis (1875) who described three types of forest humus; one consisting of well-decomposed organic matter largely incorporated with the mineral soil and containing nitrogen in the form of "nitric acid"; the other two being composed of "raw" organic remains. This subdivision has formed the basis for all subsequent schemes of classification.

P. E. Müller (1878, 1884) of Denmark was the first to look upon forest humus layers as naturally occurring biological units. He subdivided the humus layers of forest soils into two major types or groups, *mull* and *mor.* The typical representative of Müller's mull group is the earthworm mull, consisting of an intimate mixture of humus and mineral soil. It has a friable, crumby structure developed by the activity of large earthworms (*Lumbricus terrestris*) and supports a rich flora of nitrophilous geophytes. Müller's mor or raw humus group is characterized by a thick, matted layer of free organic matter, sharply delineated from the mineral soil. The vegetation includes acidophilous plants of saprophytic nature.

Since Müller published his work, there have been numerous attempts to broaden the morphological classification of humus and to relate it to the conditions of forest growth (Ebermayer, 1890; Leiningen, 1908; Ramann, 1911; Hesselman, 1926; Krauss and Grosskopf, 1928; Vater, 1928; Albert, 1929; Hackmann, 1929; Juncker, 1930; Tschermak, 1930; Romell and Heiberg, 1931; Bornebusch and Heiberg, 1935; Grosskopf, 1935). Although these efforts have increased the knowledge of humus forms, they have brought several misconceptions and unnecessary complications. Very unfortunately, most works on the classification of forest humus were permeated with the preconceived idea that a simple correlation should exist between the morphological features of humus, its chemical properties, biological composition, and the floristic or mensurational characteristics of forest cover. Advanced studies, however, have revealed a great complexity in the relationships involved.

The degree of humification and development of mull or mor types was ascribed to the reaction of the organic remains. "Sour" humus and "sweet" or "neutral" humus were used as synonyms for mor and mull humus in German, English and Russian literature. This relationship proved to be unfounded, as strongly acid mulls with a

reaction as low as pH 5.0, as well as alkaline mors with a reaction as great as pH 8.0, were observed (ROMELL and HEIBERG, 1931; ROMELL, 1932; GALLOWAY, 1940). Mull humus was presented as a material containing greater amounts of readily available nutrients than mor humus. Analysis of a large number of humus samples, as well as quartz sand culture experiments, proved the direct opposite; pure mull types showed considerably less available nutrients per unit weight than the mor types (WILDE, BURAN, and GALLOWAY, 1937). As a rule, classifications of humus disregarded the nature of underlying mineral substratum which determines chemical and, to a great extent, biological properties of humus layers. The presence of an A_1 horizon with incorporated humus was erroneously assumed to be the all-important characteristic of the biologically-active mull humus.

On the basis of observations of isolated cases, several authors proclaimed the existence of a direct correlation between the type of humus and the rate of forest growth, thus discounting the co-influence of numerous other soil factors. Under the influence of works by DARWIN (1881) and MÜLLER (1878), the "crumb mull" type, rich in earthworms, has received an undeserved reputation as an indicator of highly productive forest soils. Similarly, the misinterpretation of the process of podzolization was responsible for the often unjustified ill-fame of the raw humus. At the same time, existing classifications did not attach sufficient weight to the thickness, friability, and nutrient value of the free organic matter, properties which affect the success of natural reproduction (MOROZOV, 1912).

Classificational schemes of different authors in various countries have led to great terminological difficulties. An examination of a glossary of the terms shows that almost every expression of international use has two or more meanings and the same material is known under several names. In recent times much has been done by HEIBERG and other students of forest soils in the northeastern United States to reduce the existing confusion (HEIBERG, 1941; HEIBERG and CHANDLER, 1941).

In this book an attempt is made to present the information thus far accumulated in a simplified form and to correlate the important characteristics of humus layers with various aspects of silvicultural practice. As far as feasible, the approach of the authors of recently introduced classifications has been synchronized with the principles established by the works of earlier investigators, particularly Russian forest pedologists. The latter placed primary importance upon the nature and ecological effects of the humus layer as a whole in contrast with the recent tendency to emphasize the structural characteristics of separate sub-horizons.

Three basic types of forest humus are recognized as follows:

Earth mull: — largely an intimate mixture of amorphous organic matter and mineral soil (A_1).

Duff mull: — friable organic remains (A_0) grading into a more or less developed layer with incorporated humus (A_1).

Mor or *raw humus:* — free organic remains compressed into a tenacious horizon (A_0) overlying leached mineral soil which only in rare instances is colored by infiltrated humates.

Each of these types includes a number of morphological varieties differing in structure of incorporated layer, nature of free organic remains, thickness of duff, content of amorphous humus, reaction, and other properties. Some of these varieties, however, have a disputable silvicultural importance, as the differences in forest growth which they may produce are usually overruled by more powerful soil factors; consequently their detailed consideration does not appear to be justified.

(1) *Earth mull:* — This type is distinguished by a *thin and often interrupted or sporadic cover of litter, absence of duff, and a dark A_1*

layer with incorporated humus. The depth of the latter usually varies from 3 to 7 inches, but it may be greater than one foot. The reaction of the humus layer ranges from *p*H 5 to *p*H 8, and its content of organic matter rarely exceeds 10 per cent.

Earth mull tends to retard the process of podzolization. It is an essential profile constituent of melanized soils, but is also common as an intrazonal intrusion in soils of other forest regions. It occurs predominantly under stands of hardwoods and on sites influenced by a fairly shallow water table. The ground cover vegetation characteristic of this mull type includes mesophytic and nitrophilous "mull" plants, such as *Adiantum, Anemone, Dicentra, Hydrophyllum, Mercurialis, Sanicula,* and *Thalictrum.* The rate of growth and quality of stands are extremely variable; highly productive stands in the "central hardwood" region, inferior stands of maple and basswood on the old drift soils of Wisconsin, and struggling oaks of the prairie-forest zone may be quoted as examples. Because of the rapid decomposition of organic remains and the vigor of competing vegetation, thinnings and selective cuttings must be conducted in a very conservative manner. Forest fires are least destructive to the fertility of soils with this type of humus. The value of earth mull as a natural fertilizer is low due to the high content of mineral soil and the frequent presence of parasitic fungi.

Depending upon the structure or texture of the A_1 horizon, earth mull may be divided into a number of morphological varieties, such as "crumb mull", "grain mull", and "sandy mull".

In regions with extremely rapid decomposition of organic remains, the litter may be nearly absent and the surface soil may contain a negligible amount of incorporated humus which sometimes is difficult to detect by ocular examination. This variety may be designated as "lean mull"; it is of wide occurrence in soils of lateritic nature, particularly in red and yellow forest soils of the Atlantic Coastal Plain. As a result of erosion, fire, or grazing, lean mull may be found in other regions, especially under stands of pioneer oaks and pines.

Because the humate colloids in tropical regions are often colorless, lateritic soils generally appear to be deficient in humus. Recent investigations, however, have shown that many such soils are rich in infiltrated organic matter (VAGELER, 1933). Therefore, their surface horizons may be classified as "concealed mull".

(2) *Duff mull:* — On sites with a somewhat retarded decomposition, mull soils accumulate a *substantial layer of litter and duff having a friable consistency and a depth of not more than 2½ inches.* The underlying horizon with incorporated humus seldom exceeds a depth of 6 inches, but otherwise has the same general characteristics as in the earth mull; it may be of crumby, granular, single-grained, or other structure. The duff material of this type is distinguished by a very high biological activity and an abundant supply of nutrients in readily available form. The reaction of both free- and incorporated-humus layers varies within rather narrow limits, from *p*H 5 to *p*H 6.5.

Duff mull has podzol-forming tendencies, but its effect is much milder than that of raw humus. This transitional type is widely distributed under mixed hardwood-coniferous stands in the region of podzolic soils, and is common under oak-hickory stands of the prairie-forest. The ground cover vegetation includes a mixture of mull plants and some acidophilous plants common to podzolic soils, particularly members of the *Liliaceae,* such as

Maianthemum, Smilacina, Streptopus, Allium, Trillium, Polygonatum, Uvularia, and *Oakesia.* The conditions for natural regeneration of stands on this type are slightly less favorable than those found on the earth mull type; hence, selective logging may be carried on with somewhat greater intensity. Forest fires are decidedly detrimental to the fertility of soils with this type of humus. The duff portion can be advantageously used as a fertilizer.

In places, the zone of humus incorporation, or A_1 horizon, is only a fraction of an inch deep, or practically absent. In spite of the deficiency of incorporated humus, the occurrence of this "demelanized mull" is often correlated with stands of an exceptionally high rate of growth and vigorous reproduction of northern conifers and hardwoods. Duff material of this variety has proven an ideal fertilizing and inoculating medium for both coniferous and deciduous tree species. Selective logging should be carried on in a rather conservative manner, as the exposure of the soil will result in the rapid decomposition of the duff layer and a drastic reduction in soil fertility. Forest fires cause their greatest damage on soils with this form of humus.

The duff mull type and related morphological varieties have been previously described under the names of "moder" (RAMANN, 1911), "mar" (HESSELMAN, 1926), "surface mull" (BORNEBUSCH, 1930), and "twin mull" (ROMELL and HEIBERG, 1931). The silvicultural importance of mull humus with free organic remains, however, has often been overlooked, and the type itself confused with raw humus. The ecological differences that exist between biologically active and friable duff mull and inert or "peat-like" tenacious mor humus cannot be over-emphasized.

(3 *Mor or raw humus:* —The characteristic feature of more humus is a thick duff layer. It consists of partly decomposed remains of vegetation interwoven with the mycelia of fungi and often with roots. It is compact or tough, and ordinarily varies in thickness from 3 to 6 inches; in places it may reach a depth exceeding one foot, and cannot be readily separated from woody peat. With some exceptions, it rests directly upon the leached mineral soil. The reaction of mor, in the great majority of cases, is strongly acid, ranging from pH 5.0 to pH 3.0; however, it may also be nearly neutral or even alkaline, approaching pH 8.0.

Mor humus encourages soil leaching and is largely confined to true podzol soils which support dense stands of northern conifers. It is found sporadically in the region of tropical rain forests, particularly on sites with a high water table. In exceptional cases it may be found on soils which are only in the initial stages of podzolization. The planting of spruce outside its native region has appreciably increased the distribution of this type and hence the area of actual or potential podzol soils. The ground cover vegetation is a very reliable indicator of mor, as it is composed exclusively of acidophilous raw humus plants of saprophytic nature, such as *Vaccinium, Lycopodium, Maianthemum, Cornus canadensis, Linnaea, Clintonia,* and *Oxalis acetosella.*

Mor humus often hinders natural regeneration (SÜCHTING, 1929*a*). In order to promote the decomposition of the thick mat of organic remains, stands must be opened by logging. Sometimes the raw humus layer is broken up mechanically. As a direct fertilizer or compost ingredient, it is considerably more valuable than earth mull, but is inferior to duff mull. Ground fires, destroying the raw humus, deplete the fertility of the soil, but

in some instances they exert a beneficial effect upon the natural regeneration of stands. Soils with mor humus should be scrupulously avoided in the selection of nursery sites or farm land, since the cultivation and subsequent decomposition of free organic remains will leave a sterile quartzose residue.

Depending upon the composition of the humus layer, several varieties of mor may be recognized, *viz.*, "matted mor", "fibrous mor", "laminated mor", etc.

In the boreal region of the North American and Eurasian continents, the organic layer assumes the form of a thin but firm crust of lichens, xerophytic mosses, and needles. Such "crust mor" is confined to sandy soils which are too poor to support heath shrubs. It has an extremely acid reaction approaching *p*H 3.0. The adverse influences of this type on forest growth are well known, from the descriptions of the "Yag" type of the Russian (Morozov, 1912) and the "Cladonia" type of the Finnish foresters (Cajander, 1926).

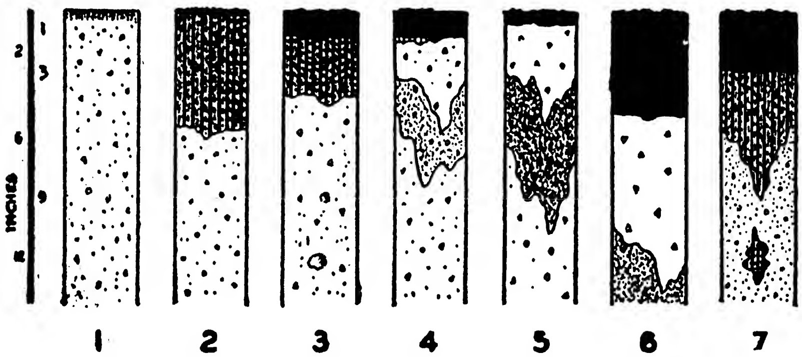


Figure 19. — Diagram of representative morphological varieties of forest humus: 1. Lean mull; 2. Earth mull; 3. Duff mull; 4. Demelanized or bleached mull; 5. Crust mor; 6. Matted mor; 7. Infiltrated mor. Incorporated humus is indicated by vertical lines, raw or free organic matter by solid black.

In podzol soils with impeded drainage, raw humus may be underlain by a dark A_1 horizon with "washed in" or infiltrated humus. The tongues and flakes of humus may extend to a depth greater than one foot. On wet gley soils of heavy texture the infiltrated horizon attains the black color and plastic consistency of muck or "sapropel" (Stebutt, 1930). The forest cover on these "infiltrated mors" is characterized by the vigorous development of the shrub understory and the presence of mosses, ferns, sedges, and other water-loving ground vegetation. Natural reproduction proceeds more rapidly than on other forms of mor, but the desirable species may be easily suppressed by weed trees and shrubs if the stand is cut too heavily.

Exposed limestone outcrops and calcareous deposits in the podzol region are sometimes covered with a thick dark-brown layer of alkaline raw humus or "rendzina mor". The reaction of the organic matter usually fluctuates between *p*H 7.0 and *p*H 8.0, but it may be as low as *p*H 6.5. The forest stands are of inferior quality and are composed chiefly of conifers. Northern white cedar, *Thuja occidentalis,* is the predominant species in the United States. The ground cover includes typical saprophytic plants occurring commonly on strongly acid soils (Galloway, 1940). Since the organic layers rest upon calcareous strata, their destruction through fire, logging, or erosion converts the land into unproductive barrens. The use of the duff layer as fertilizer is objectionable because of its high content of calcium and magnesium carbonates. The lime bearing strata of high mountains develop "alpine humus" (Leiningen, 1908; Tschermak, 1921; Heimburger, 1934), which is closely related to rendzina mor.

Figure 19 presents schematically the important features of humus morphology.

Chemical and Biological Properties of Humus in Relation to Its Morphology or Degree of Decomposition: — Because of differences in degree of decomposition, humus types exhibit specific proportions of lignin, cellulose, proteins, fats, resins, and similar groups of constituents. The significant fractions of these groups may be isolated and determined quantitatively after extraction with water, ether, alcohol, strong acids, and other reagents (WAKSMAN, 1938). The relative contents of these fractions brings out not only the differences between the types of humus, but also the differences between a certain humus type and the original residue from which it was derived. Unfortunately, this type of analysis is too complicated to be employed in routine determinations. Table 11 illustrates the chemical composition of several types of forest humus occurring in the podzol region.

TABLE 11. — *Proximate Chemical Composition of Different Types of Forest Humus* (H. M. GALLOWAY and W. E. PATZER): —

CONSTITUENTS	Acid raw humus	Alkaline raw humus	Duff mull	Crumb mull
	Per cent of dry material on ash-free basis*			
Ether soluble fraction	3.42	0.26	2.94	0.46
Hot water soluble fraction	5.22	2.42	3.78	1.83
Alcohol soluble fraction	4.65	2.12	2.00	3.17
Hemicelluloses	6.84	7.82	3.35	2.94
Cellulose	6.08	2.21	4.07	1.69
Lignin	41.51	32.72	39.71	31.16
Crude protein	11.11	12.41	11.60	19.02
Total accounted for	78.83	59.96	67.45	60.27

* Ash contents: Acid raw humus — 4.55%; alkaline raw humus — 14.46%; Duff mull — 12.85%; crumb mull — 90.12%.

The rate of organic matter decomposition is broadly correlated with the activity of microorganisms as manifested by the liberation of carbon dioxide, the consumption of oxygen, the evolution of heat of fermentation, or the release of soluble nitrogen (MELIN, 1930; BORNEBUSCH, 1930; ROMELL, 1932; GLØMME, 1932). A quantitative record of these processes may serve to indicate the general nature of organic remains (NĚMEC, 1928). It should be noted, however, that natural environment is an extremely important factor in the activity of organisms and, hence, the results of biological investigations of humus under optimum laboratory conditions have but relative significance.

Nutrient Content and Exchange Properties of Humus: — The nutrient content of humus is a function of three variables: type of humus, nature of underlying substratum, and composition of forest stand (Plate 6). Mull types having a high volume weight show considerably lower concentration of nutrients than mor or raw humus types. Heavy soils derived from parent materials rich in minerals, produce humus with a high content of nutrients, whereas sandy or siliceous soils produce humus poor in nutrients. Light demanding species, particularly pines, tend to accumulate less nutrients in their litter than do tolerant trees, such as spruce, maple and basswood (SEREX, 1917; ALWAY, KITTREDGE and METHLEY, 1933). The relative

contents of nutrients in different types of humus are presented in figure 20. Although humus is a factor of great complexity, involving physico-chemical, biological and catalytic aspects, a close correlation has been shown to exist between the nutrient content of humus and the growth of forest seedlings under controlled conditions (WILDE, BURAN, and GALLOWAY, 1937).

Base exchange capacity is closely related to the content of lignin-like substances, and may serve as an indicator of the degree of humus decom-

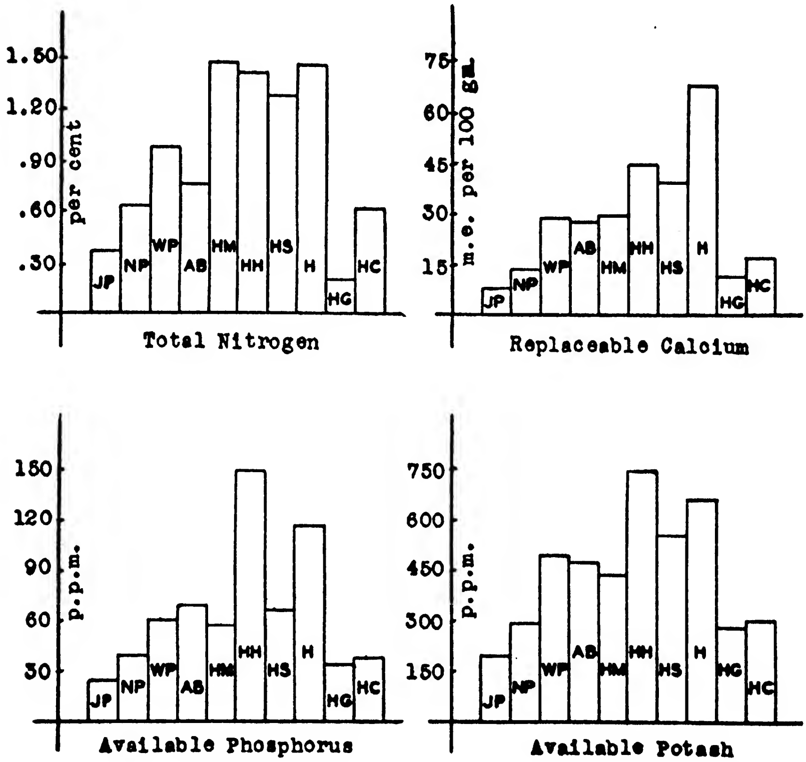


FIGURE 20. — Contents of nitrogen, calcium, phosphorus, and potash in different types of organic remains from upland forest.

JP—jack pine duff; NP—Norway pine duff; WP—white pine duff; AB—aspen-birch duff; HM—hemlock duff; HH—hardwood-hemlock duff; HS—hardwood-spruce-fir duff; H—hardwood duff; HG—hardwood grain mull humus; HC—hardwood crumb mull humus.

position. The base exchange capacity of raw humus ranges from 40 to 100 m.e. per 100 g. The base exchange capacity of mull humus is seldom greater than 30 m.e. per 100 g. because of the high content of mineral matter; however, the exchange capacity of the organic fraction itself may exceed 200 m.e. per 100 g. The base exchange capacity also serves as an index of the buffering effect of humus (PLICE, 1934).

Aside from mineral nutrients, humus contains specific organic compounds which are beneficial to the growth of higher plants. These "growth-promoting" or "growth-regulating" substances, known as "phyto-hormones" or "auxins", are produced by microorganisms in the course of decomposition of plant remains. The stimulation of root growth on cuttings of conifers

and other trees by Beta indole acetic acid and other auxins is a striking example of hormone action. Vitamin B_1 or thiamin is of major and far-reaching significance in the general development and vigor of plants. It is characteristic of growth substances that they bring about their physiological effects while present in minute concentrations; it is chiefly on this basis that they are differentiated from plant nutrients (WENT, 1935; BONNER, 1937; SCHOPFER, 1943).

Humus with iron forms some compounds in which this element is available to plants and microorganisms in soils of neutral or moderately alkaline reaction. This property of humus is of particular importance in relation to the nutrition of forest trees, old stands as well as nursery stock. The discoloration or "chlorosis" of seed beds is a common occurrence on slightly acid or alkaline nursery soils depleted in organic matter. Similar beneficial effects of humus upon the availability of phosphorus and other nutrients have been observed on numerous occasions (PRIANISCHNIKOFF, 1923).

Silvicultural Importance of Humus: — Regardless of the origin or morphological form, humus fulfills in the soil four important functions; it improves physical properties of the soil, provides nitrogen and other plant food, absorbs mineral salts, and increases the availability of nutrients through its exchange and catalytic effects.

The statement that "Humus is the spirit of the soil" (KNOX, 1915) is quite applicable to soils of forest nurseries. In no other branch of plant production is a deficiency of humus manifested with such sharpness as it is in forest nurseries. Forest trees, especially conifers, develop in their youth on a purely organic layer of forest debris, and thus acquire more or less pronounced saprophytic tendencies. No crop residues are left in the soil of the nursery because even the root systems of seedlings are removed. Continuous weeding and cultivation, artificial irrigation, and additions of commercial fertilizers promote biological activity and rapid decomposition of organic matter. Under these conditions, the maintenance of an adequate supply of humus may require regular additions of organic remains to the soil (WILDE and HULL, 1937).

Until recently research and reforestation practice have been neglecting the role which organic matter plays in the survival and growth of plantations. This indifference may be attributed to comparatively limited experience in the reforestation of old cut-over areas, the complicating co-influence of mineral colloids, occurrence of organic matter as incorporated humus as well as surface litter, and certain analytical difficulties in the determination of organic matter.

According to the agronomist's saying, "Nitrogen spells organic matter". In leached or sandy forest soils, with their revolving fertility renewed through the annual leaf fall, the organic matter appears to be synonymous with the content of all nutrients. Moreover, organic matter retains considerable amounts of water, and plantations on soils rich in humus are likely to be less subject to drought injury than humus-deficient soils. A study of plantations in the podzol region has indicated a pronounced increase in the rate of height growth of trees due to the higher content of organic matter (Figure 21). A general tendency for the increased survival of seedlings was also observed on soils high in humus (WILDE and PATZER, 1940).

Since the influence of organic matter supplements, within certain limits, the effect of mineral colloids, a coordinated consideration of both of these factors provides a wider basis for the selection of planting sites, and, at the same time, gives more assurance of success.

General observations indicate that the absorbing or base exchange effects of soil organic matter are at least two and one-half times as great as those of fine soil material, *i.e.*, material less than 0.05 mm. in diameter. Hence, as regards these effects, it may be estimated for practical purposes that 1% of organic matter is equivalent to 2.5% of fine soil material. This implies that a considerably lower content of mineral colloids is adequate for successful planting on soils high in organic matter. Figure 22

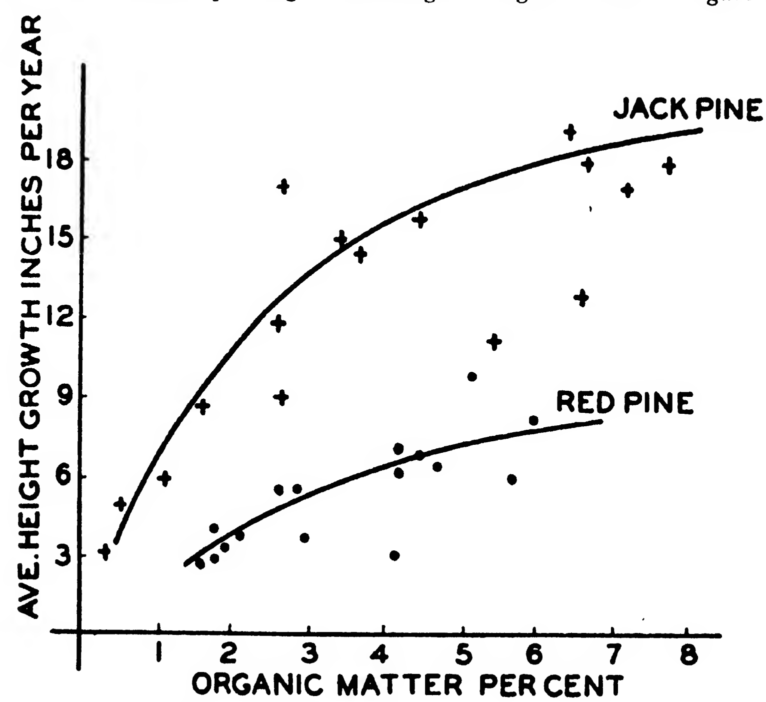


FIGURE 21.—Relation of height growth of jack pine and red pine plantations to the content of organic matter in podzolic sandy soils of northern Wisconsin. The general trend is indicated by free-hand curves.

presents an example of a scheme of planting possibilities for four coniferous species under Wisconsin climatic conditions and for soils not influenced by ground water. The slanted lines represent the minimum acceptable ranges of fine soil material and organic matter for each species. The ordinate and abscissa values for any point on a species line give the minimum acceptable values of each constituent for that species. Therefore, the lines of species which intersect perpendiculars erected from the coordinates, or fall within the area enclosed by the perpendiculars, indicate that these species are suitable for planting on the soil in question. For example, if the soil analyzes 20% of silt and clay and 2.7% of organic matter, then the site is suitable to jack pine, red pine, and white pine, but not white spruce. The

graphs may also be used in a somewhat different manner. Suppose the soil of a large outwash tract is known to contain about 10% of silt and clay particles; then the sites suitable to red pine should have at least 3% of organic matter. A study of local plantations is a prerequisite for the establishment of standards suitable for other species and climatic conditions.

The determination of organic matter content may also serve as an index of soil depletion resulting from grazing, burning, removal of litter, or erosion, and may be very useful in the management of woodlot soils.

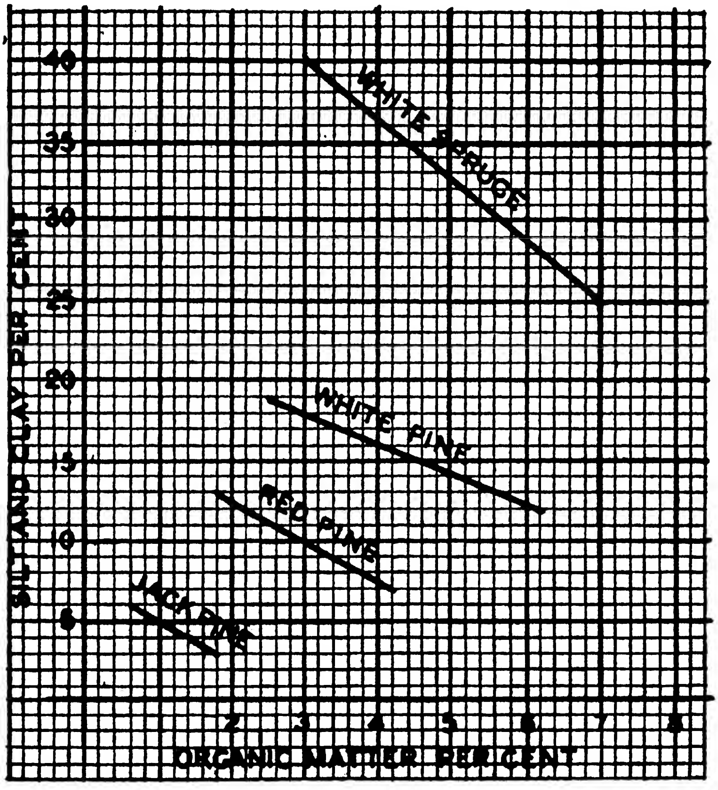


FIGURE 22. — Planting possibilities of northern conifers in relation to soil texture and content of organic matter under Wisconsin conditions. The lines of species which touch the intersection of perpendiculars erected from the coordinates, or fall within the area enclosed by the perpendiculars, indicate that these species are suitable for planting on the soil in question.

Determination of Soil Organic Matter: — The rapid and simple determination of soil organic matter may be accomplished by means of the colorimetric method based on the reduction of chromic ions to the chromous state (WILDE, 1942).

Pass the air-dry soil through a 20-mesh screen onto a clean dry paper. Mix the sample thoroughly and fill the measuring spoon heaping full with soil. Pack down tightly with a spatula and strike off level with the top of the measuring spoon. If the soil is low or medium in organic matter, use measuring spoon calibrated to deliver a one-half gram sample; with soils high in organic matter, use a quarter-gram spoon. Experience will soon teach which size of sample is preferable. In the event the calibrated spoons are not available, the sample may be weighed out.

Transfer sample into a 50 ml Erlenmeyer "Pyrex" flask and add exactly 2 ml of potassium dichromate solution using an Ostwald-Folin transfer pipette. Empty the pipette completely by blowing out the last few drops. Add 20 ml of sulfuric-phosphoric acid mixture. Insert a thermometer in the flask and digest the contents for five minutes on an electric stove, or any other suitable source of heat, at a temperature between 160 and 170 degrees C. Ordinarily, the contents of six or more flasks are digested simultaneously.

Remove flask from the hot plate and cool in the air until temperature is 140 degrees C, or less. Place digestion flask slowly into a cold water bath. Change the water several times to speed up the cooling. When the solution reaches a temperature of 50 degrees C, dilute the contents with 20 ml of water. Mix the water with the digested liquid by swirling the flask. Place flask again in the cold water bath and allow to cool. Decant off 20 ml of the solution into a 6 x 1 inch "Pyrex" test tube marked at 20 ml and match the color with standard solutions or a Cenco-Wilde color scale. The comparison should be made in daylight against a sheet of white onionskin paper fastened on a window facing north. When a half-gram sample is used, the readings give directly the percentages of organic matter. If a quarter-gram sample is used, the reading must be multiplied by two.

For more exacting work the readings can be made against ground glass with a constant light source. A black cardboard tube, one inch in diameter, may also be advantageously employed as a comparator; such a tube should have two opposite openings ½ and ¾ inches in diameter, the larger opening sealed with a double sheet of tracing cloth.

Reagents:

Potassium dichromate solution. Dissolve 9.807 grams of oven-dry reagent grade potassium dichromate in 75 ml of water. Add 1 ml of concentrated sulfuric acid and make up to 100 ml in a volumetric flask. Keep the solution in a tightly stoppered container.

Sulfuric-phosphoric acid mixture. Add 4 parts by volume of concentrated sulfuric acid, CP grade, to 1 part of 85% phosphoric acid, USP grade.

Standard solutions. Dissolve 1.875 grams of anhydrous dextrose, reagent grade, in 100 ml of distilled water. Use a Mohr micro-pipette to place in a series of 1 x 6-inch Pyrex digestion tubes the dextrose solution, in amounts beginning with 0.1 ml and increasing 0.1 ml in each consecutive tube. Use 10 tubes, leaving one without dextrose to serve as a blank. Add to each tube 1 ml of potassium dichromate and 9 ml of sulfuric-phosphoric acid mixture. The reduction of chromic ions to the chromous state produces a variation of color ranging from bright orange to bluish-green. Allow solutions to cool and dilute with distilled water to a volume of 20 ml. These standards, based on 0.5-gram sample, correspond to the following percentages of soil organic matter: 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 and 4.5.

The standard solutions may be used for several days if kept in tightly stoppered vials. These standards may be replaced by a permanent color chart, manufactured by the Central Scientific Company, Chicago, Illinois.

Because soil organic matter occurs in the form of surface debris as well as humus incorporated to various depths with the soil, the samples for analysis should be collected by means of a tube which removes a representative cross-section of the entire surface soil layer to a definite depth, usually 7 inches.

Chapter X

SOIL-FOREST TYPES

"The distribution of vegetation is influenced by climate and governed by soil."
G. F. MOROZOV

Origin and Significance of the Concept "Soil-Forest Types": — Although systematic investigations of soil-forest relationships are less than one century old, the knowledge of the specific soil-forest units is of an ancient date (KRUEDENER, 1927). Long before scientists attempted to disclose the factors responsible for the distribution of forest vegetation, Indians in America and Mongolian tribes in Eurasia had a remarkably clear concept of the adaptation and productivity of various types of forest soils. These people of the wilderness were dependent for their livelihood upon game, berries, mushrooms, and other products of the forest. Wood, bark of trees, bast fibers, sap, forest herbs—all these played a vital part in the maintenance of the household. This dependence on the "growth of the soil" led to an intimate understanding of the factors influencing the productivity of land, distribution of both trees and ground cover plants, quality of wood, susceptibility of forest to fire, abundance of game, and other conditions. Speaking of habits of the Ojibwa Indians, SMITH (1932) states: "They make full use of everything that occurs with them, except the adventive or introduced plants. They recognize regular types of soil as sources of their medicinal plants. Sandy meadows, sandy wastes, lakes, still ponds, swamps, upland swamps, rocky openings in the forest, evergreen forests, and hardwood forests all are searched for distinctive plants."

In numerous instances the interrelationships of soil, plants and animals, and even the human beings have penetrated deeply into the life of the white man, and have found a masterful expression in works of great writers. A few lines from the "Markens Grøde" of HAMSUN may be quoted as an excellent example; they describe the environment of the desolate "Almenning", no man's land in the author's native Norway:

"Man moves along the western side of a valley; wooded ground with hardwood trees among the spruce and pine, and grass beneath. Hours of this, and twilight is falling, but his ear catches the faint purl of running water, and it heartens him like the voice of a living thing . . . . He moves down and there is a green hillside; far below, a glimpse of the stream, and a hare bounding across. The man nods his head, as it were approvingly—the stream is not so broad but that a hare may cross it at a bound. A white grouse sitting close upon its nest starts up at his feet with an angry hiss, and he nods again: feathered game and fur—a good spot this. Heather, bilberry, and cloudberry cover the ground; there are tiny ferns, and the seven-pointed star flowers of the wintergreen. Here and there he stops to dig with an iron tool, and finds good mould, or humus soil, manured with the rotted wood and fallen leaves of a thousand years. He nods, to say that he has found himself a place to stay and live . . . ."

Trained forester as well as soil expert may bow before such a laconic and yet profound description of land and life.

Brief descriptions of some of the more important soil-forest associations found in different parts of the world are given in this chapter (Plate 4). An

attempt was made to cover a sufficiently wide range of physiographic conditions and to combine the descrptions of the individual types into groups characterized by a comparative similarity of conditions. Such an arrangement allows one to observe the parallelism in the development of geographically distant biocentic units, particularly those of the Eurasian and American continents.

The specific objectives of this outline are to show the varying effect of soil properties under different climatic conditions and to illustrate by means of concrete examples the universal applicability of the fundamental laws governing the distribution and growth of vegetation. These basic laws form the essentials of not only silvicultural practice, but the entire science of plant ecology. The problems of soil-forest types have received attention from numerous writers on silviculture in both the Eurasian and North American continents, particularly GUTOROVICH, 1897; KRUEDENER, 1903; MOROZOV, 1905; ZON, 1906; CLEMENTS, 1909; LEININGEN, 1922; CAJANDER, 1926; RUBNER, 1927; KLIKA, 1929; TAMM, 1930; SUKACHEV, 1930; and BURGER, 1931.

Pine Barrens: —

(1) *Scotch pine barrens of Northern Russia:* — The snow-like floor of reindeer moss and other lichens sharply differentiates this type from the rest of the forest. It occupies small areas on sand dunes and sandy ridges along rivers, but is widely distributed.

The soil is a weakly podzolized or podzolic sand deficient in mineral colloids and organic matter. The humus layer is thin, crust-like, and acid. Both the content of available nutrients and the water holding capacity of the soil are at a minimum. The stands are composed of pure Scotch pine of very low productivity. The average height at 100 years does not exceed 50 feet. The density of stands ranges from 40 to 60 per cent. The trees have crooked stems and the wood is suitable only for distillation. The type is subject to severe fires. Burned-over areas come back slowly to Scotch pine. The ground cover consists of different species of *Cladonia,* chiefly reindeer moss, *C. rangiferina,* xerophytic grasses, *Carex ericetosum, Festuca ovina,* and *Deschampsia flexuosa,* and a few species of low shrubs, particularly *Arctostaphylos uva-ursi,* and *Vaccinium vitis-idaea.* The low shrubs occur sporadically. In rare instances *Juniperus communis* and *Rosa acicularis* form a skeletal understory (TKACHENKO, 1911; KRUEDENER, 1927).

"Pinetum cladinosum" or "Cladonia site" of Scandinavia, "Heide" of Germany, and "Jack pine barrens" of North America are very closely related to the reindeer moss barrens of Russia. The conditions found in Maryland present somewhat greater deviation from the general pattern and are briefly outlined.

(2) *Virginia pine barrens of Maryland:* — The soil is dry coarse sand, largely of siliceous origin. It is poor in nutrients and has a very low content of organic matter. The deficiency of humus is in part due to repeated burning. The predominant member of sparse forest cover is Virginia or "scrub" pine. The scattered associates include shortleaf pine and drouth resistant oaks. Red cedar, dogwood, black gum and persimmon occur in the understory. The productivity of stands is very low and the wood is suitable only for fuel. The ground cover is composed of several species of *Cladonia,*

Dicranum scoparium, D. condensatum, and *Leucobryum glaucum.* This cover of lichens and mosses is dotted with *Solidago juncea, Andropogon ternarius,* and other xerophytic grasses (SHREVE *et al.,* 1910).

Pine on Podzolic Sands: —

(1) *Scotch pine on glacial sands of Northern Finland:* — This type occurs on moderately podzolized sands or light sandy loams of level and pitted outwash. It is widely distributed in the northern part of the country. The forest consists of Scotch pine mixed with birch, aspen, and spruce. Pine attains a fair rate of growth, and produces wood of satisfactory quality. The ground cover includes abundant mosses, especially *Hylocomium* and *Dicranum,* and a number of low shrubs, *viz., Empetrum nigrum, Vaccinium myrtillus, Vaccinium vitis-idaea* and *Calluna vulgaris.* This association is referred to as the Empetrum-Myrtillus type (CAJANDER, 1926).

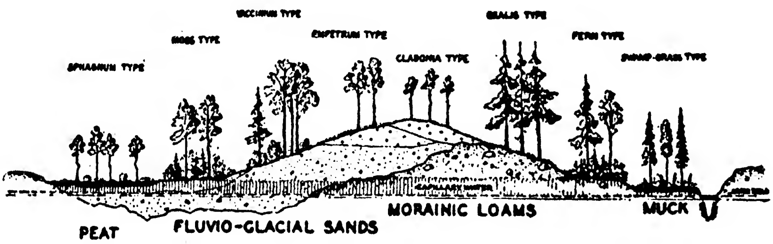


FIGURE 23. — Distribution of typical ground cover plants in relation to soils and topography in northern Finland. (A generalized scheme).

Figure 23 gives an example of the distribution of some typical ground cover associations of Northern Finland in relation to soils and topography.

(2) *Scotch pine on sandy terraces of Briansk Region, Central Russia:* — The level or slightly undulating topography of the river terraces is intersected by knolls and depressions of aeolian and fluvial origin. The soil is slightly podzolized and has a well developed dark horizon with incorporated humus attaining a thickness of 8 inches. The leached layer is often concealed but the accumulative horizon has a pronounced orange color and a slight cementation; it grades into lemon colored, deep, coarse sand which at a depth of four feet is underlain by loam. Stored water in the substratum greatly benefits the growth of forest stands. The forest cover is composed of Scotch pine with some birch. Ground vegetation includes *Calamagrostis, Vaccinium vitis-idaea, V. myrtillus, Pteris aquilina (Pteridium latiusculum), Stellaria, Potentilla, Solidago, Pyrola media, Rubus saxatillis, Convallaria majalis,* and *Lycopodium complanatum.* Scotch pine has a fair productivity, reaching an average height of 90 feet and a yield of 500 cubic feet per acre at the age of 100 years. It produces high grade timber. This type is referred to as "Pine Plains" (MOROZOV, 1930).

(3) *Red and White pine on glacial sands of the Lake States Region, U. S. A.:* — Podzolic sands occupy a considerable portion of the glacial outwash and partly assorted sandy deposits in the northern portions of Minnesota, Wisconsin, and Michigan. These soils show pronounced light grey leached and reddish-brown accumulative horizons; the accumulative layer

is often compacted, but not cemented. The content of silt and clay particles varies from 8 to 15 percent. The reaction of the soil is seldom higher than *p*H 5.5 (Wilde, 1932*b*).

The forest cover includes white pine, red pine, some jack pine, several oak species, aspen and, in places, paper birch. The shrub story is composed of hazel, raspberry, blackberry, fly honeysuckle, and a few other shrubs. The ground cover consists predominantly of wintergreen, *Gaultheria procumbens,* shin leaf, *Pyrola americana,* trailing arbutus, *Epigaea repens,* blueberries, *Vaccinium pennsylvanicum* and *V. canadensis,* Canada mayflower, *Maianthemum canadense,* sweet fern, *Myrica asplenifolia,* and some bracken fern, *Pteridium latiusculum.* Sweet fern occurs predominantly on slightly podzolized sands, while the presence of Canada mayflower indicates advanced podzolization. In the language of practical foresters this type is known as "wintergreen site". Comprehensive descriptions of forest growth on these sites were given at early dates by Mayr (1890) and Roth (1898). Figure 24 presents a general scheme of the relation of soils and forests in the podzol region of the Lake States (Wilde, 1933).

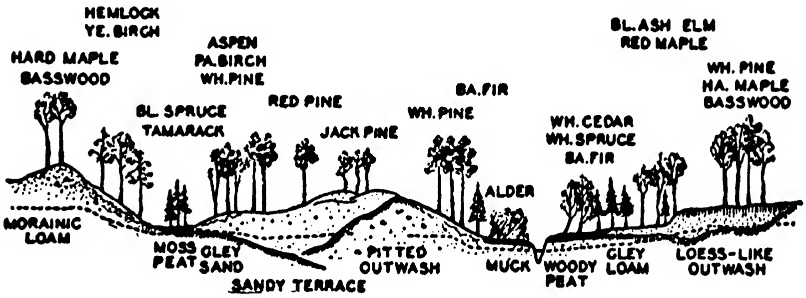


Figure 24. — Distribution of tree species in relation to the water table, texture of the soil, and podzolization in the glaciated area of the podzol region of the Lake States.

Spruce and Hardwoods on Podzolic Loams: —

Leached but not cemented loams form the backbone of forest production; they are extensively distributed and well adapted to a number of valuable tree species, particularly spruce. A large portion of the podzolic loams is confined to rough areas of mountains and glacial moraines, *i.e.*, land which is submarginal from the standpoint of agriculture.

(1) *Spruce stands on morainic ridges of the Upper Volga Basin, Russia:* — The well-drained, podzolized loams are often underlain by heavy iron-bearing or glauconitic strata. From 70 to 90 per cent of the stand is made up of spruce, the remainder being white birch with some pine and aspen. The spruce reaches 85 feet in height and 15 inches in diameter at the age of 150 to 200 years. The yields are as high as 400 cubic feet per acre. The wood is of excellent quality and is not subject to heart-rot diseases. Ground cover vegetation is sparse and includes *Hypnum, Oxalis, Maianthemum, Trientalis, Polypodium dryopteris, Aspidium filix-mas,* with some *Lycopodium, Linnaea borealis, Rubus saxatilis,* and *Vaccinium myrtillus* (Kruedener, 1927; Morozov, 1930).

(2) *Hardwood-coniferous stands on glacial till of Adirondack Mountains, New York, U. S. A.:* — The soil profile of this type is a transition between true podzol and weakly podzolized or "mull" soils. The organic layer is composed of granular or friable debris; it is underlain by a leached podzolic horizon which grades into a dark chocolate-brown accumulative layer high in organic matter. The B horizon is of great depth and gradually merges with the unaltered substratum.

Forest stands are composed of hard maple, beech, yellow birch, red spruce, and occasionally hemlock. The stands attain a rather high productivity; red spruce reaches particularly good development in association with hardwoods. There is usually an abundant reproduction of beech and hard maple (Bray, 1930; Heimburger, 1934). The shrub understory includes *Acer pennsylvanicum, Acer spicatum, Lonicera canadensis, Viburnum*

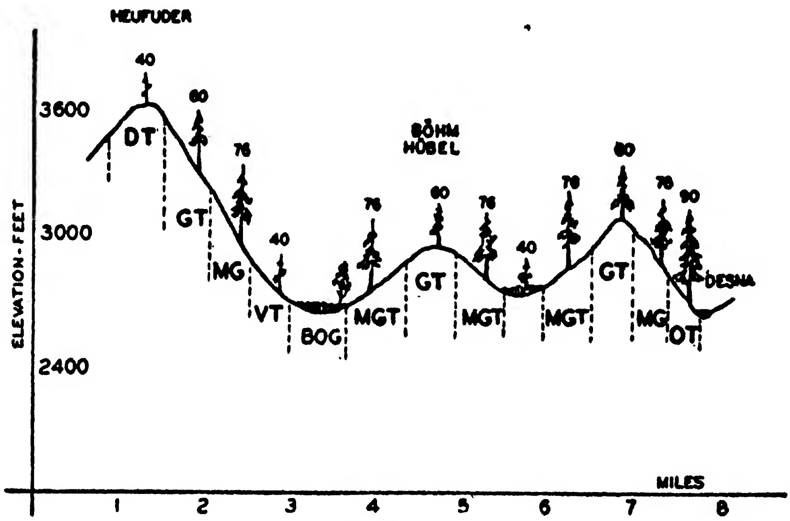


Figure 25. — Soil-forest types of Iser Mountains: DT—Deschampsia type, GT—Grass type, MGT—Moss-grass type, VT—Vaccinium type, OT—Oxalis type. The numbers indicate the average height of forest stands at 100 years. (*After* Jaroslav Müller).

alnifolium, and *Taxus canadensis. Viburnum* is very characteristic for this type. The ground cover consists of *Oxalis acetosella, Aralia nudicaulis, Medeola virginiana, Streptopus roseus, Smilacina racemosa, Oakesia sessilifolia, Polygonatum biflorum, Maianthemum canadense, Clintonia borealis, Tiarella cordifolia, Mitchella repens, Aspidium intermedium,* and *Lycopodium lucidulum. Oxalis* appears to be the most typical plant indicator, and is especially abundant on more podzolized areas. The greatest part of the mixed hardwood-coniferous forest of the Adirondacks belongs to this type.

(3) *Spruce stands of the lower slopes of Iser Mountains, Bohemia:* — Shallow podzolic soils of granitic origin occur on moderate slopes at altitudes from 2,500 to 3,000 feet. Spruce stands attain high productivity chiefly due to the position of the ground water level which permits utilization of capillary

water. The average height and diameter at 100 years are 75 feet and 16 inches, respectively. Ground cover is composed mainly of *Dicranum scoparium, Polytrichum commune, P. strictum, Hylocomium splendens, Sphagnum spp.*, some other mosses, *Calamagrostis villosa, C. arundinacea and Deschampsia flexuosa. Oxalis acetosella* and *Vaccinium myrtillus* occur sporadically. The grasses do not form a solid cover. The site may be called "moss-grass" type. Figure 25 indicates its relative position (Müller, 1936).

Although the stands of this type regenerate fairly well naturally, reproduction cutting should be carried on in a very conservative manner. A considerable opening of the stand may result in a rise of the ground water level, decreased aeration of soil, and spread of Sphagnum mosses.

(4) *Coniferous-hardwood type of the lower slopes of Manchuria:*— This type is adapted to the altitudes lower than 2,500 feet, and is best developed on slopes not exceeding 15° gradient. The soils of loam texture are largely of deluvial nature and are somewhat podzolized. The A_1 horizon reaches a thickness of 8 inches and is underlain by a little-differentiated A_2B horizon, characterized by a yellowish-gray color. The dominant species of the forest cover is *Picea ajanensis.* This is mixed with *Betula plotyphylla, Acer manshuricum, Tilia manshurica, Ulmus montana, Abies nephrolepis,* and *Pinus manshurica.* The stands have a fairly high productivity. The understory includes *Corylus manshurica, Acer manshuricum* and *Tilia manshurica.* The ground cover is characterized by *Oxalis acetosella, Maianthemum bifolium and Lycopodium spp.* (Ivashkevitch, 1916).

Hardwoods on Melanized or Mull Loams:—

(1) *Beech uplands of Bohemia:*—This is one of the few hardwood types of Central Europe that has in places preserved its original composition. It is found chiefly on the lower slopes of mountains or hills. A calcareous origin of soil material and influence of seepage water appear to be essential features of this type.

A thin layer of litter overlays a dark horizon of mull humus of a coarse or fine crumby structure. The humus layer merges into dark-brown mineral soil which becomes finer in texture and lighter in color with depth but exhibits no distinct podzolic features. The reaction of the soil profile is either neutral or slightly acid. The forest cover is composed of beech with some European fir, Norway spruce, and hornbeam; other hardwoods occur only incidentally. The stands show a high rate of growth and a considerable density. However, with advanced age beech and especially conifers are often affected by heart-rot. The presence of beech appears to be the chief factor preventing the leaching of soil. The shrub story includes *Acer campestre, Evonymus, Cornus,* and many other species, but their occurrence is sporadic. Very often the understory is made up entirely of prolific beech reproduction. The ground cover is characterized by *Asperula odorata, Asarum europaeum, Mercurialis perennis, Anemone nemorosa, Luzula pilosa, Dentaria, Oxalis acetosella, Impatiens,* and sometimes *Hepatica triloba* (Sigmond, 1924).

(2) *Hardwood slopes of Adirondack Region, U. S. A.:*—This type is found at the foot of talus slopes and steep mountain sides, and its occur-

rence is often correlated with outcrops of limestone. Seeping ground water from the mountain sides is usually responsible for an abundant supply of soil moisture. The type is primarily confined to southeastern exposures, where favorable conditions of local climate may be expected. The soil profile very rarely has a distinguishable leached horizon. It is overlain by a mull humus of varying acidity, but of high lime content and high nitrifying capacity. The hardwood stands have a high productivity and are composed of sugar maple, beech, white ash, elm, basswood, and black cherry with some yellow birch, hornbeam, and balsam fir in the understory. Red spruce occurs only in small numbers; it is of very poor quality and usually infected by fungi. This forest is often used as a "sugar bush", and in such cases the percentage of sugar maple is increased artificially. The common shrubs are *Dirca palustris, Cornus alternifolia, Prunus virginiana,* and *Ribes spp.* The ground cover consists of *Arisaema triphyllum, Laportea canadensis, Adiantum pedatum, Dicentra canadensis, Dentaria diphylla, Galium lanceolatum, Impatiens spp., Osmorhiza Claytoni, Panax quinquefolium, Caulophyllum thalictroides, Claytonia virginica,* and several species of ferns (Heimburger, 1934).

Prairie Forest: —

The soils in the transitional prairie-forest zone present a picture of a stubborn struggle between two antagonistic formations; a struggle which involves not only plants, but animals and lower organisms as well. Grass kills young trees by depriving them of moisture; trees suppress grass by over-shading and by the action of decaying litter. Prairie animals devour forest seed; forest birds plant them again and again. Damping-off fungi destroy forest seedlings; mycorrhizae gradually infest prairie areas and stimulate tree growth. This struggle does not end even when the forest canopy is closed over the prairie soil. For years, perhaps centuries, trees may suffer here from an excess of carbonates, malnutrition, grass competition, root-rot diseases, and rodent damage. In time, however, forest humus with its powerful acidifying, reducing, and solvent action removes carbonates, checks diseases, eliminates grass, and thus transforms prairie soil into a reasonably productive forest soil.

(1) *Degraded chernozem of Dnieper watershed, Southern Russia:* — This region is located in a sub-humid prairie climate. The soil is a slightly degraded chernozem derived from loess. The sporadic forest stands extend into the prairie. They are composed chiefly of summer oak, *Q. pedunculata,* and have an understory of maple and basswood. The productivity of these stands is extremely low; the height of dominant oaks is approximately 60 feet. Ground cover is characterized by abundant *Sisymbrium alliaria,* and this association is classed as *Quercetum sisymbrianum* (Prokhorov, 1906; Vorobiov and Pogrebniak, 1929).

As distance from the prairie increases, degradation of the soil becomes more pronounced and the forest growth improves to such an extent that individual trees reach a height of 80 feet. Simultaneously the stands of oak are enriched by ash. *Stellaria holostea, Asarum europaeum,* and *Carex spp.* appear in the ground cover. A particularly noticeable improvement of the forest growth is observed on the lower slopes and in cove bottoms where

degraded chernozems or dark groods are replaced by leached groods and podzolic soils (Figure 26).

(2) *Lime prairies of Mississippi, U. S. A.:* — The state of Mississippi is located in a warm and humid climate. Red and yellow soils of a lateritic substratum are prevalent. "Lime prairies" are confined to a belt of black clays or clay loams formed on weathered or "rotten" Cretaceous limestone. These level rendzina-like soils are highly productive agriculturally, but support only a sparse growth of trees, mainly post oak and jack oak (Hilgard, 1906). Red cedar, clumps of crab apple, honey locust, and thickets of Chickasaw plum are found occasionally. The oaks, although sporadically distributed, attain considerable dimensions. This soil exerts a striking influence upon the form of trees, especially post oaks (Figure 27).

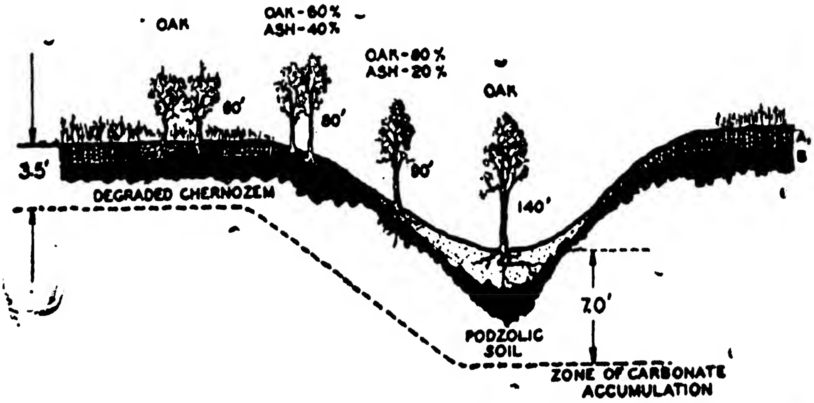


Figure 26. — Relation of forest growth to soils in southern Russia. The numbers indicate the average height of forest stands.

(3) *Rendzinas of southern Wisconsin, U. S. A.:* — This portion of Wisconsin lies in a rather cool and fairly humid climate of a distinctly podzolic nature. The prairie soils found in this region have no horizon of lime accumulation and are usually of an acid reaction (Whitson, 1927).

Juvenile rendzinas or humus-calcareous soils are confined to eroded slopes of limestone bluffs. The southern and southwestern exposures are particularly conducive to the development of this soil type. The upper portion of the soil profile consists of a thin layer of litter and a black horizon with incorporated humus. This horizon is essentially similar to that of prairie soils. The depth of the humus layer seldom exceeds 6 inches, although it may be greater than one foot. The humus layer usually grades into detritus of disintegrated limestone. Soils in an advanced stage of development, or "degraded rendzinas", exhibit faint differentiation of their profile into a light colored leached layer and a brownish accumulative horizon.

The predominant tree species is bur oak, *Quercus macrocarpa,* occurring alone or in association with other oaks, *Q. alba, Q. velutina,* and *Q. borealis,* shagbark hickory, *Carya ovata,* and in rare cases black walnut, *Juglans nigra.* The pioneer species include paper birch, *Betula papyrifera,* aspen, *Populus tremuloides,* red cedar, *Juniperus virginiana,* sumac, *Rhus glabra,* hazel, *Corylus americana,* and sometimes the introduced black locust,

Robinia pseudoacacia. The ground cover is characterized by the presence of prairie species, *e.g., Andropogon scoparius, A. fureatus, Sorghastrum nutans,* and *Silphium laciniatum.* The incidental associates are *Rhus toxicodendron, Parthenocissus vitacea, Vitis vulpina,* and *Poa pratensis.* The stands have a low rate of growth and park-like appearance. Logging and especially pasturing convert this type into barrens and dangerous centers of acute erosion.

Coniferous-Hardwood Stands on Gley Loams: —

(1) *Spruce flats of Northern Russia:* — The soils of this type are of a loam or clay loam texture, strongly podzolized and acid. They are underlain by a heavy clay loam substratum of morainic origin. At a rather shal-

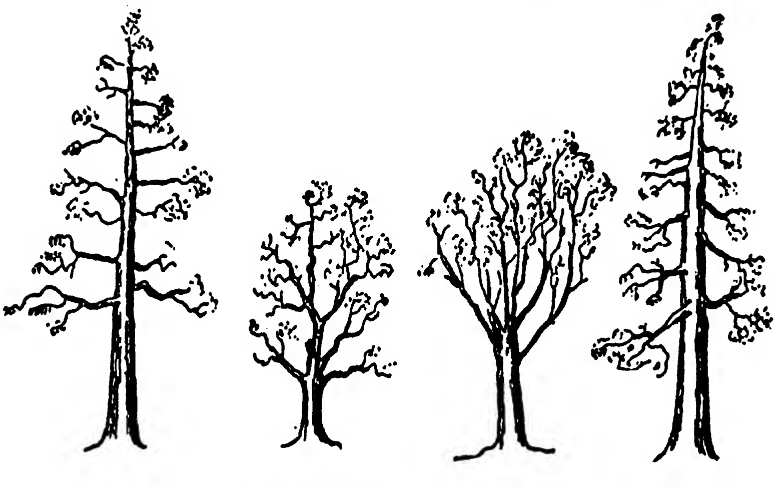


FIGURE 27. — Extreme forms of post oak on different soils. (*After* HILGARD).

low depth the subsoil is water-logged and exhibits mottling. These plateaus occupy large areas forming a transition between well-drained morainic soils and swamps. The forest stands are composed of spruce with sparse white birch. The stems are short and are covered with lichens. The root systems are superficial. The usual density of the stands is 60 per cent. The height and diameter are 55 feet and 8 inches, respectively, at 150 years. Half of the stand is usually infested with heart-rot fungi. After fire this type becomes waste land and it is commonly 10 or 15 years before a few clumps of brushy birch, aspen, willow and mountain ash begin to appear. The ground cover is composed of *Polytrichum, Hypnum,* and *Sphagnum* among which are scattered *Equisetum silvaticum* and *Vaccinium* spp. This type is known under the names of "Rovniad" and "Picetum polytrichosum" (MOROZOV, 1930).

(2) *Balsam fir flats of northern Wisconsin, U. S. A.:* — The soil is derived from heavy glacial drift. The upper layer of soil is strongly leached and grades at a depth of 2 feet into a sticky and mottled clay. The reaction in the entire profile fluctuates between pH 4.2 and 5.0. The forest cover is domi-

nated by balsam fir growing in association with white spruce, hard maple, red maple, rock elm, black ash, and yellow birch. Occasionally fir and spruce form pure coniferous stands. Trees have a low rate of growth, suffer from windfall and are attacked by parasitic fungi. Hard maple is especially affected by heart-rot. Sporadic growth of shrubs includes dogwood, mountain ash, currant, and gooseberry. The ground is covered by *Polytrichum, Mnium,* and *Hylocomium* spp., with some *Leucobryum* and *Sphagnum.* The mosses tend to form a solid mat. Other members of the association are sedges, horse tail, *Equisetum silvaticum,* bunchberry, *Cornus canadensis,* twin flower, *Linnaea borealis,* star flower, *Trientalis borealis,* and bedstraw, *Galium* spp. (WILDE, 1932*b*).

The growth of trees improves considerably on elevated portions of topography with a deeper ground water level; the ground cover on such sites is characterized by ferns and mull plants.

Conifers on Moss Peat: —

The ground cover of acid moss bogs preserves its composition throughout the entire northern hemisphere. However, the trees of these sites exhibit a rather puzzling dissimilarity in Europe, Asia, and America.

(1) *Scotch pine swamps of Finland:* — The peat consists of the remains of Sphagnum mosses, sedges, and heath plants. The stands are composed of struggling Scotch pine. The ground association includes *Sphagnum, Ledum palustre, Calluna vulgaris, Empetrum nigrum, Vaccinium uliginosum, V. vitis-idaea, Andromeda polyfolia, Cassandra* (*Chamaedaphne*) *calyculata, Oxycoccos palustris, Rubus chamaemorus, Eriophorum vaginatum, Scirpus* and *Carex* spp. *Betula nana* occurs in the understory. The presence of many xerophytic plants in the ground cover is noteworthy (CAJANDER, 1926).

(2) *Larch swamps of Manchuria:* — The stands on Sphagnum peat are composed of larch with some spruce, pine, and birch. The density of the stands seldom exceeds 70 per cent but the total yields are comparatively high. The ground cover is composed of *Sphagnum, Eriophorum* and *Equisetum.* The presence of Siberian larch on these sites in warm valleys is a riddle since this species ordinarily occurs on the rocky ridges of Asiatic mountains at elevations as high as 5,000 feet (IVASHKEVITCH, 1916).

(3) *Black spruce-Tamarack swamps of the Lake States Region, U. S. A.:* — The upper layer of peat consists of slightly decomposed mosses which grade into sedges and remains of other swamp vegetation. The peat is extremely acid, the reaction of the top soil being as low as *p*H 3.5. The only trees occurring on this site are black spruce and tamarack. They form either pure or mixed stands. *Betula pumila* is a common associate. Ground cover consists of *Sphagnum* and *Polytrichum* species, *Chamaedaphne calyculata, Ledum groenlandicum, Kalmia polifolia, Andromeda glaucophylla, Linnaea borealis, Chiogenes hispidula, Vaccinium macrocarpon, Sarracenia purpurea,* and plants common on dry sandy soils, such as sweet fern, wintergreen and reindeer moss (WILDE, 1932*b*).

Chapter XI

FOREST SOIL SURVEY

"Ohne floristische Arbeit — keine pedologischen Untersuchungen; und vice versa ohne pedologische keine floristische. Suum cuique."
ARTHUR FREIHERR VON KRUEDENER

Purpose and Technique of Forest Soil Survey: — In growing agricutural crops much can be done to secure satisfactory conditions of the soil for the crop selected. Drainage can be improved, the tilth of the soil modified by cultivation, and additional plant food supplied by fertilizers. In silviculture, however, such modifications are, as a rule, impracticable. The only way to secure a maximum income from forest enterprise is to plant, or to encourage by means of partial cuttings, the species which are best adapted to a given set of conditions.

The required information on the climate, topography, ground water and soil, is obtained by means of a special study and mapping called "forest soil survey". Because this survey usually deals with a whole complex of ecological or site factors (VATER, 1916), as well as the soil, it may be also referred to as "forest site survey" or "forest land survey".

The survey of forest land constitutes the first and probably most important step in the organization of a forest tract for planned management. It defines the areas adapted to silviculture or other uses, and delineates the soils suitable for planting to different tree species or for logging by different cutting methods. It forms the basis for the construction of yield tables, calculation of the annual cut, and determination of expected fiancial returns. Moreover, soil survey often proves invaluable in the appraisal of land for sale or exchange, taxation, and settlement of damage suits. In many instances, the survey provides a rational framework for subdivision of a forest with regard not only to silvicultural practice, but also to transportation, logging operations, and fire control.

In surveying land for forestry purposes, the area is traversed back and forth at fixed intervals which vary from one-quarter to one-eighth of a mile, depending upon the nature of the land and intensity of management. The distance is measured by careful pacing while the direction is kept by means of a hand compass. Variations in soil and other conditions are recorded on the original field map and in the notebook together with remarks about specific characteristics of land, vegetation, and silvicultural treatments. In order to locate exact site boundaries, offsets are taken from the traverse line. Offsets are particularly important in hilly areas or tracts with dense forest growth. The details of mapping technique are discussed by BEAMAN (1928), KRASIUK (1931), and KELLOGG (1937). Recently aerial photographs have become available and are used as base maps in soil survey work (MILLAR, 1932). They greatly facilitate detailed mapping.

Use of Reports and Maps of Previous Surveys: — During the past forty years, state and federal agencies have carried out numerous soil surveys (U.S.D.A., 1938). The results of these surveys, published as bulletins

and maps, are of great assistance in forest soil surveys as well as in the solution of forest management problems (Kittredge, 1928; Veatch, 1932; Wilde and Scholz, 1934; Donahue, 1936).

As would be expected, the technique of soil surveying has advanced considerably in the course of time. The intensity and accuracy of mapping have been increased and the interpretation of soil features has been placed on a broader scientific basis. Because of this, recent soil maps and survey reports are much more serviceable to foresters than those issued earlier. The older maps contain much valuable information, however, and with some additional field work may be converted into maps of planting sites or maps showing potential possibilities of forest management. This conversion may require either consolidation or further subdivision of the types originally surveyed (Sampson, 1930; Hough, 1942).

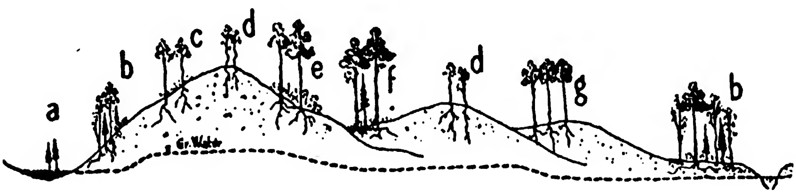


Figure 28. — Forest sites encountered on partly assorted glacial sandy deposits of recent drift derived from granitic rocks (Vilas sandy loam, Langlade County, Wisconsin).

(a) Stagnant pothole; Black spruce-tamarack (*Ledum-Chamaedaphne*) site; (b) Swamp-border podzol: Pine-aspen-birch-balsam fir (*Cornus-Rubus*) site; (c) Slightly podzolized denuded sand, steep southern exposure: Jack pine-red pine (*Myrica-Gaultheria*) site; (d) Barren gravelly sandy ridge: Jack pine (*Cladonia-Arctostaphylos*) site; (e) Podzolized sandy loam, northern exposure: Red pine-white pine (*Vaccinium-Gaultheria*) site; (f) Sandy loam podzol with ortstein: White pine-balsam fir (*Vaccinium-Cornus*) site; (g) Weakly podzolized sand, considerably assorted: Red pine (*Arctostaphylos-Ceanothus*) site.

The classifications of the early soil surveys were based entirely upon the possibilities of agricultural land utilization. This approach is not always in agreement with the interests of forest management. In many cases, the conditions of forest growth are essentially the same on a number of soil types of different agricultural importance, *viz.*, stony or stone-free soils, loam or silt loam soils, soils of glacial or residual origin, and so forth. On the other hand, soil types of agricultural classifications may not be sufficiently uniform from an ecological standpoint to satisfy the needs of forestry practice. This is particularly true of soils having minor agricultural value, such as wind blown sands, light sandy outwash soils, soils of rough morainic deposits, poorly drained mineral soils and peat soils. Types of this nature, though uniformly unproductive agriculturally, may show considerable variation in forest growth. These variations may be affected by topography, leaching, drainage, nature of organic remains, soil texture, or other conditions (Wilde, 1932*a*).

In surveying land for agricultural use the topography is usually classified into different types, such as level, undulating, rolling or rough (Whitson, 1927). In forest land surveys, however, it is necessary to consider not the types of topography, but its elements such as hilltop, ridge, plateau, slope, valley, and basin. This difference in the classification of topographical features is likely to cause most of the difficulties when an attempt is made to adapt the data of a general soil survey to forestry purposes. Since the composition of the soil profile varies depending upon its location on top of the hill, on the slope, or in the depression, surveys which consider only the general lay of the land, may neglect essential differences in the type of organic matter, degree of acidity, leaching, content of nutrients, and other important soil properties (Novák and Zvorykin, 1927; Zavalishin and Pronevich, 1928).

As a concrete example, stony unassorted morainic loams of northern Wisconsin appear on older reconnaissance soil maps under the name "Kennan loam". As reforestation experience has shown, this type may include two silviculturally important phases: strongly leached, often cemented podzol loams with raw humus and a reaction as low as *p*H 4.0; unleached, friable loams with mull humus and a reaction approaching *p*H 7.0. These two phases require different methods of selective logging, as well as different species for planting and must be carefully differentiated by means of an additional survey. Figure 28 illustrates a more complex condition found in northern Wisconsin on rough glacial deposits of sandy texture (Vilas sandy loam). This example emphasizes the importance of topographic features in the distribution of forest vegetation and, hence, in the selection of planting sites for various tree species.

Soils containing less than 12 per cent of silt and clay are of minor value for farming. Therefore, such soils appear in agricultural classifications as a single textural type, for instance Plainfield sand or Vilas sand. From the standpoint of reforestation, however, small differences in the content of fine separates in such sandy soils are of great importance. For instance, in northern regions, soils containing less than 5 per cent of silt and clay are not suitable for commercial reforestation; soils having 5 to 10 per cent of fine material are suitable only for planting pioneer species, for instance jack pine; slightly heavier soils are adapted to more exacting pines, such as red pine. Thus, in the surveying of sandy soils for forestry purposes an especially detailed textural classification is required (Wilde, 1932*a*.).

On the other hand, detailed knowledge of the colloidal content in heavy soils is only of minor significance to the forester. As far as texture is concerned, such soils are capable of supporting almost any tree species. In other words, in heavy soils the colloidal content ceases to be a limiting factor, and several textural types of agricultural classifications, such as loam, silt loam, and clay loam may often be regarded as one forest soil type. Detailed classification of heavy soil is more meaningful if made on the basis of their structure, internal drainage, and aeration.

Some agricultural soil surveys differentiate the soil types according to the amount of stones per acre, as stoniness is a critical factor in agricultural land utilization. In such a classification some types may be divided into as many as four sub-types based upon the degree of stoniness. From the standpoint of silviculture, the presence of large stones is of significance because it eliminates the possibility of furrow planting, and, hence should be recorded in forest soil mapping. At the same time, detailed classification of stoniness is of little importance because stones do not interfere with spot planting.

Degree of Accuracy and Cost of Survey: — The survey of land for forestry purposes is generally confined to specific areas selected for intensive forest management. It seldom covers an area larger than one township, or 36 square miles, and is ordinarily carried on by traversing land at intervals of one-eighth of a mile. The area mapped as a separate type may be as small as two acres. This great intensity is justifiable because a plantation or selectively logged stand represents a long time investment.

The survey of forest sites is relatively expensive, its cost often running as high as 10 cents per acre. Such an outlay, however, is sound as the planting of trees includes not only the cost of seedlings and planting, but also the expense of taxes, fire protection, and silvicultural care, with compound interest on all this money for a period of many years. An insufficiently detailed survey, and subsequent mislocated planting, therefore, may result in great losses. The minimum cost of planting is 7 to 10 dollars, and the minimum for the total investment is 30 to 40 dollars per acre. Thus, the cost of planting one township is nearly a quarter of a million dollars, and the total investment may exceed a million dollars. The cost of a detailed soil survey of one township is about 2,000 dollars which constitutes but 0.2 of one per cent of the total investment. These figures show clearly that it is advisable to spend the necessary amount of money on a careful selection of planting sites and thus make certain that the decisive step in reforestation is taken in the right direction.

Equipment Used in Surveys of Forest Land: — Below are listed the most important items of equipment required in forest soil surveys:

Spades and soil augers, forester's compasses, tally counters, field-sheet holders with rubber bands (tatum-holders) and supply of field sheets, graduated rulers, triangles, paper, pencils, pens, erasers, ink, and thumbtacks.

Hypsometer, diameter tape, increment borer, folding rule for soil profile measurements, soil testing outfits, bags for soil samples, blotters and press for the collection of plants. Aerial photographs and other available maps. Plane table with accessories when there is no base map and an accurate survey of roads is required. An accurate tire pressure gauge in case a car with speedometer is used in measuring distances.

The chief of the surveying crew must make sure that all the equipment needed is in sufficient quantity and good order so as to prevent unnecessary and often embarrassing delay of work.

Correlation of Soils and Forest Growth as a Basis for Establishing Soil Types: — The greatest fault of the early soil surveys was the establishment of soil types on the basis of theoretical, speculative assumptions instead of observations of soils and growth of plants in nature. As a result of this, in many instances "The soil surveyor knew the difference in soil properties when the vegetation did not." To overcome these discrepancies, the abstract classifications were gradually subjected to critical ecological analysis, using as an indicator the distribution of natural plant associations, and their rate of growth. As a result of these studies, there was recently advanced a theory of ecological equivalents, based upon the fact that the floristic composition of a stand and its rate of growth on a given site are a complete expression of all the productive forces of that environment. Thus, the condition of vegetation was accepted as the only sound classificational basis and the soil and other environment factors were correlated with the distribution and growth of plants. Simultaneously, the mere "soil" classifications were replaced by broader and more elaborate ecological "site" classifications (Kruedener, 1916; Vater, 1916; Cajander, 1926). Since the condition of the forest association is the only object of importance to the forester, the ecological relationships form the foundation of present day surveys for forestry purposes. On the basis of these principles the general procedure of the establishment of types to be surveyed is outlined below.

The soil surveyor selects in nature a sufficient number of sample areas, supporting forest stands of similar composition of trees, shrubs and ground vegetation. These areas are usually selected within the surveyed tract, but in case of cut-over or burned-over land may be located in the surrounding territory. The outstanding floristic and mensurational characteristics of the sample areas are recorded. The determination of the average rate of growth, and the identification of the typical plant indicators are of particular importance in this phase of the study. A careful investigation of the soil profile is made at the same time that the mensuration and botanical records are taken. Then statistical treatment and comparison of all the data obtained are used to outline the principal ecological units. These may be further subdivided in accordance with the needs of reforestation practice. For instance, the same silt loam mull soil, supporting a hardwood stand with a ground cover of maidenhair fern, may be divided into two types, namely;

level outwash silt loam, allowing for furrow planting, and rough stony morainic silt loam, requesting spot planting. The areas separated in a forest soil survey must have differences of practical significance in their adaptation to tree species, rate of stand growth, possibilities of natural reproduction, technique of planting, or methods of thinning and logging.

The actual surveying of land is usually influenced by the rule of "practical balance" requiring separation of *small areas* characterized by *great differences,* and *large areas* characterized by *small differences.* According to this rule, frost pockets or potholes 2 acres or less in size may be mapped separately in a sand region, while areas of a light sandy loam can be overlooked unless they attain a size of 5 or more acres. The mapping of small but conspicuous areas, such as leatherleaf bogs or rock outcrops, is often desirable not because of importance of the areas themselves, but because of their value as landmarks.

Nomenclature: — Soil types or sites are designated on the basis of location of the representative area of the type, morphological properties, suitability for certain tree species, or characteristic ground cover.

Naming soil types after a certain town or locality, such as *Plainfield sand,* or *Kennan loam,* is the easiest way to classify a great variety of soil types. It eliminates the necessity of using long descriptive names such as "slightly podzolized sandy loam over clay", and prevents possible confusion of soil types in different regions. However, a map provided with a legend of this kind cannot be interpreted without an accompanying report, and is inconvenient in the field. This system has thus far failed to attain popularity among practical foresters, although it may prove useful in the future.

On the basis of morphological features the soils may be designated as *barren sand, leached sand, outwash mull loam, morainic loam podzol, wet loam, mottled loam, structural clay,* etc. This is the most direct and descriptive method, and should be used at least on the basic soil map, provided the survey is confined to a limited area. If the area surveyed has a great variety of soil types, nomenclature often involves a combination of textural, genetical, geological and hydrological characteristics.

Designation of sites according to characteristic tree species such as *Jack pine site, Spruce site, Lowland hardwood site,* is most useful on the map showing planting possibilities. Such a map is usually constructed from the basic soil map by combining soil types suitable for planting to the same species, or the same mixture of species. This system meets with the enthusiastic approval of practical foresters, because of its simplicity and directness. However, the presentation of the entire survey in terms of planting sites often may not be desirable as there may be great differences in productivity and response to management of soils suitable for the planting of the same species, or supporting stands of the same composition.

The use of the characteristic ground cover as a basis for nomenclature, such as *Vaccinium site, Fern site,* or *Woodsorrel site,* is very convenient in surveys of extensive forest tracts supporting virgin or mature forests. Also, a map of floristic sites may be very helpful in carrying on the planting, thinning and selective logging program in regions with diversified topography. In surveying tracts with large areas of cut-over land or young second growth stands a purely floristic legend may lead to serious misinterpretations and confusion (Kruedener, 1916).

In the majority of instances it will be found desirable to present the results of the survey on a map showing soil types classified on the basis of their morphology. This map may be further supplemented by the map of ecological sites, based upon adaptation of land to certain tree species, or upon characteristic ground cover vegetation.

Report on Survey of Forest Soils: — The map of forest soil types, or forest sites, must be accompanied by a report written in clear, carefully worded language. This report must contain the following information:

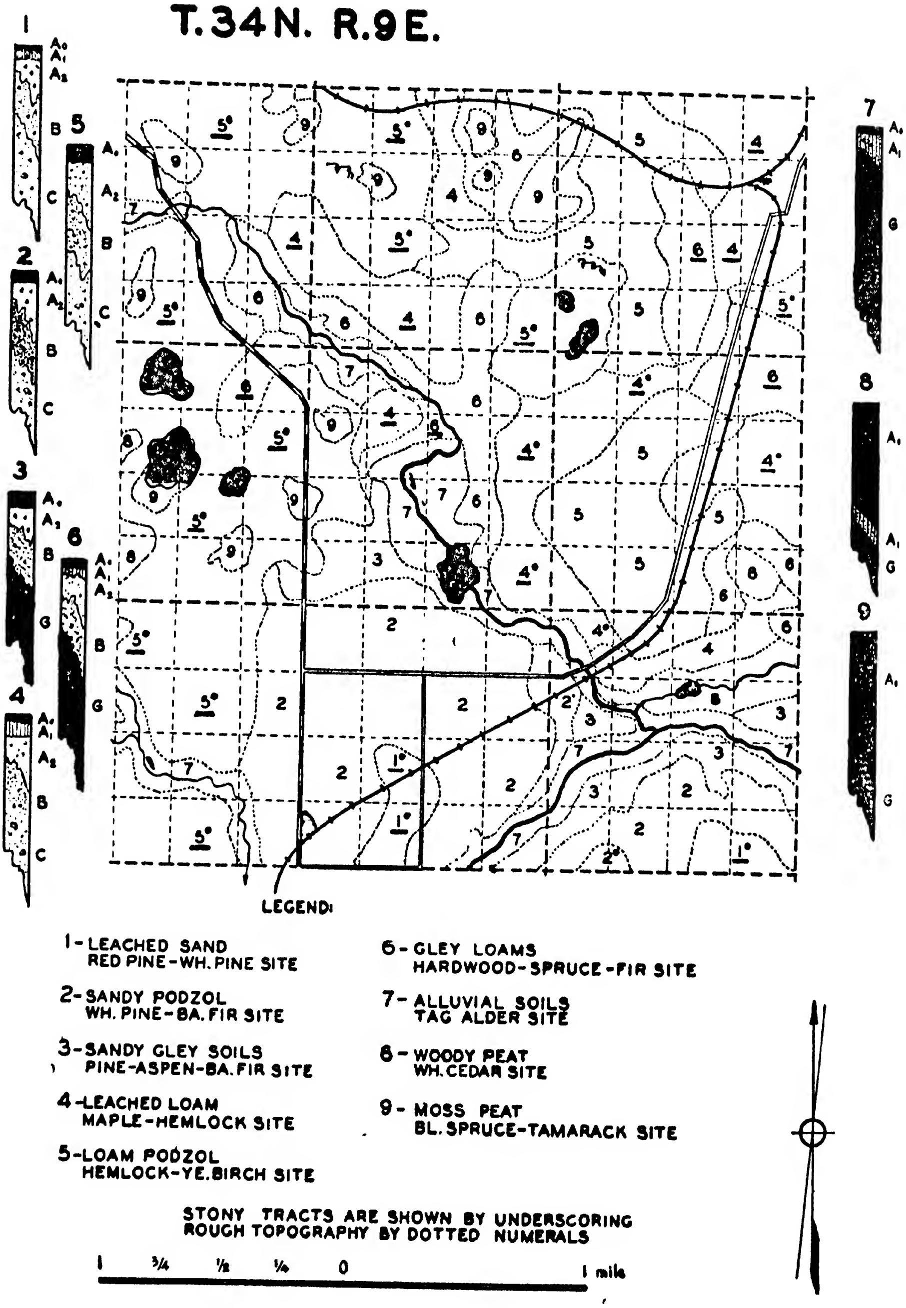


FIGURE 29. — An example of a forest soil map.

(1) *General characteristics of the area surveyed:* — Geographic location, variation in altitude, topography, presence of water bodies, rivers and creeks, ownership, transportation facilities, extent of local wood-using industry, importance of area in recreation and wild life management, forest fire hazards, and other data of practical significance.

(2) *Climate:* — Data on mean annual, minimum, maximum, and growing season temperatures, occurrence of early spring and late fall frosts; annual and growing season precipitation, frequency and duration of drought periods; number of cloudy days per growing season, air humidity, precipitation-temperature or precipitation-saturation deficit ratios, and direction of prevailing winds.

(3) *Geology:* —Nature of surface formations and underlying rocks; mineralogical composition of parent soil material; types and extent of erosion processes.

(4) *Vegetation:* — List of forest trees, important shrubs and characteristic ground cover associations present on the area.

(5) *Technique of mapping employed:* — Reliability of controls, intervals at which the land was traversed, size of area recognized as individual type or site, general accuracy of survey.

(6) *Soil and site classification:* — Soil types or sites recognized, methods of soil study, number of soil profiles investigated, frequency of borings, designation of horizons, use of forest cover and ground vegetation as a guide in the delineation of soil types.

(7) *Detailed description of types surveyed:* — Composition of soil profile, nature and amount of organic remains, content of colloids, depth to ground water, moisture of the surface soil layers, aeration, reaction, and available nutrients. Composition of main forest stand, understory, shrub layer, and ground vegetation. Approximate rate of growth. Possibilities of natural seed reproduction, ability of certain species to sprout, competition of weed species. Suitable systems of silvicultural management; types of thinnings, release cuttings or selective logging. Species important in soil conservation, game and fish protection, reduction of fire hazard, as seed trees and nurse trees. Possibilities of artificial reforestation; species suitable for planting, and suitable methods of planting.

It is advisable to attach to the report a schematic drawing of representative soil profiles. Such a drawing should indicate the minimum and the maximum depth of separate genetical horizons, emphasizing especially impervious layers or hardpan, strata with a high content of carbonates, and water-logged gley layers. (Novák and Zvorykin, 1927).

Figure 29 presents an example of a forest soil map.

Use of Soil Survey Data in Forest Management: — The soil types delineated by the survey usually serve as the units of forest management, called "compartments" or "lots". Depending on circumstances, the forester in charge may either combine several soil types occupying small areas into one compartment, or may subdivide extensive areas of the same type into a number of compartments. When a compartment includes a number of soil types, each is treated as a "subcompartment". The subdivision into subcompartments may also be necessary because of differences in the origin, age, or composition of forest cover (Roth, 1914; Chapman, 1931).

The compartments are customarily designated by Arabic numbers and subcompartments by small letters. Such designation helps greatly to keep a permanent orderly record of all the data pertinent to the growth and silvicultural treatment of individual forest stands. Table 12 gives an example of stand inventory comprising a part of a management plan.

In the event that the forest tract is composed of several large areas having different conditions of physiography and forest cover, such areas are treated as independent broad management units referred to as "working circles". Usually working circles are managed on different rotations and

under different silvicultural systems. Heavy morainic deposits with hardwood stands attaining suitable lumber dimensions at the age of 80 years, and sandy outwash with jack pine available for pulp at 40 years may be given as examples of two working circles.

TABLE 12. — *Stand Inventory:* —

Unit	Composition of soil	Composition of stand	Area acres	Age yrs.	Site index	Remarks
7a	Podzolic sandy loam; level outwash	0.8 Wh. pine[4], Red pine[1], Aspen[5]....	17.3	22	70	Release cutting due
b	"	Recently burned area	5.5	..	..	To be planted to red pine in 1945
c	Swamp-border sandy podzol	0.7 Wh. pine[3], Wh. spruce[1], ba. fir[2], aspen[4]	3.4	22	50	No treatment until 1950

Survey and Subdivision of Forest Tracts in Mountain Regions: — In a country with sharply pronounced relief, especially in high mountains, the conditions of exposure and gradient play just as important a part in forest growth as do the properties of soil. Because all physical factors of forest growth, including climate, ground water, and soil, are affected by topography, an intimate knowledge of its influences is essential for proper surveying and subdivision of forest tracts (WILDE and SCHOLZ, 1930).

According to PASSARGE (1929), topography is classified into three principal types:

(1). *Positive topography,* including the portions of relief subject to denudation, such as peaks, ridges, hill tops, hog backs, and higher slopes;

(2). *Neutral topography,* including nearly horizontal formations, such as plains, terraces, and plateaus;

(3). *Negative topography,* including the portions of relief subject to deposition of eroded materials, such as lower slopes, valleys, canyons, and basins. Valleys have a definite outlet for run-off, and show some retranslocation of deposited matter. Basins have no outlet and are areas of final deposition.

The positive portions of topography receive much light and heat; they are exposed to the wind and are often deficient in moisture. In consequence, positive topography is predisposed to the invasion of light-demanding and xerophytic species. Negative topography has opposite conditions and tends to support shade-tolerant, mesophytic or hydrophytic species.

The distribution of trees in hilly regions is further influenced by the exposure or orientation of slopes. In general, the exposures important from an ecological standpoint are: northeastern, northwestern, southwestern, and southeastern (WARMING, 1895; WAGNER, 1923). The northeastern exposure is the darkest and coolest. The southwestern exposure is the warmest and receives the most light. The other two exposures occupy intermediate positions. While the moisture content of different exposures varies greatly with the direction of rain-bearing or dry winds, in most cases, the northeastern and northwestern slopes retain a greater amount of water because of lower temperatures, moderate evaporation, and retarded melting of snow.

The effect of exposure upon the distribution and growth of trees is especially marked when trees approach the boundaries of their natural range. Pine forests at high elevations are confined to southern slopes, while spruce and hemlock along the southern boundary of their native region occupy northern exposures. In the prairie-forest transition, white birch of satisfactory quality is found on northeastern slopes, whereas oaks in the podzol region make their best growth on southwestern exposures. As a rule, forest species in marginal zones tend to occupy the slopes facing their native regions. Under certain conditions, such as exist in the Rocky Mountains, the shifting of a species in artificial reforestation from western to eastern slopes is equivelent ecologically to a translocation of several hundred miles in a region of plains.

The variation of environmental influences on slopes of different exposures becomes more pronounced with increase in gradient. Aside from climatic factors, the steepness of slope affects the intensity of erosion, the productivity of forest soils, and their adaptation to silvicultural utilization. The following classification expresses the principal types of land with regard to their degree of slope or topographical outline:

Slope in Degrees	Type of Topography	Type of Slope
0-5	level or undulating	
5-15	gently rolling	gentle
15-30	rolling	moderate
30-45	hilly	steep
45 or more	rough	precipitous

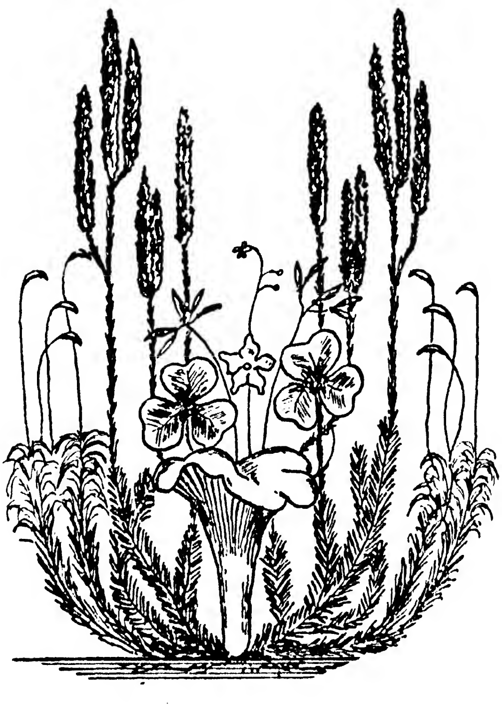
The best conditions for silvicultural practice are found on level land and gentle slopes. Moderate slopes are also satisfactory for silviculture, but plowing the land for planting is inconvenient. Steep slopes are subject to intensive erosion and require selective logging. Precipitous slopes are characterized by a highly destructive run-off and scarcity of fine soil material; as a rule, forestry as a commercial enterprise cannot be practiced in such localities.

Soils overlying positive topography are subject to denudation, *i.e.* constant impoverishment in fine soil material, humus, and soluble salts. Neutral topography is characterized by a comparative equilibrium of weathered debris and a balanced state of soil fertility. Negative topography exerts both beneficial and detrimental influences upon soils; the lower slopes and depressions accumulate water and fertilizing products of erosion, but the effect of these fertility factors is offset at a certain point by impeded drainage.

The rate of forest growth on a topographical complex is often expressed by a curve correlated with the three major fertility factors: moisture, aeration, and nutrients. The elevated points of topography, depleted in moisture and nutrients, produce low yields of timber. As the elevation decreases, the trees have a tendency to "level the relief with their crowns" (Morozov, 1912). After reaching the optimum soil conditions, the growth drops abruptly in accordance with rapidly decreasing aeration. This relationship is the key to the survey or classification of mountainous and hilly forest lands.

From the earliest days of organized silviculture in European countries, topography served as a basis for subdividing forest tracts. According to old practice, the boundaries of compartments usually coincided with ridges, streams, and roads (Guttenberg, 1911). A subdivision of this kind often disregarded the uniformity of soil and forest vegetation within the compartment and led to unnecessary complications in forest management. In

recent times the work of soil scientists and ecologists has led to the subdivision of forest tracts into compartments of ecologically-uniform topographical features (Wilde, 1929*a*). In the subdivision of forests on an ecological basis, compartment boundaries do not necessarily coincide with logging roads or other permanent objects. Such boundaries can be marked in nature by blazing trees or setting a limited number of posts, but often they are sufficiently indicated by differences in the composition of the forest. In many instances, the physical subdivision can be economically supplemented by construction of roads and fire lanes along the ecological boundaries. In time, the subdivision of a forest tract, managed on a natural basis, will inevitably be brought into agreement with the distribution of forest types.



Chapter XII

SOILS AND TREE PLANTING

"Probieren geht über Studieren; aber erst studieren, dann probieren."
HEINRICH MAYR

Reforestation Program: — The reforestation program in a given region includes the following major steps: the selection of species suitable for planting, production of planting stock, selection of planting sites, and the actual planting.

Selection of Tree Species: — Species for planting are usually selected by the chief administrative officer responsible for the reforestation of a large territory, such as a state or a national forest. The conditions of climate and soils, resistance to insects and diseases, and the commercial importance of the species are the principal points considered in the selection (BÜHLER, 1922; DENGLER, 1930; TOUMEY and KORSTIAN, 1931; HEIBERG, 1933).

In order to facilitate the location of nurseries and the proper distribution of stock, extensive regions are sometimes roughly divided into several areas adapted to a certain combination of tree species or a specific type of reforestation. Figure 30 gives an example of such broad division on the basis of climate and soils.

The seed of the chosen species is acquired from reliable sources and used either for direct seeding or for raising planting stock in nurseries. In the majority of cases the selection of trees to be planted is confined to native species, the seed or cuttings of which are collected in the same region, or from areas ecologically similar to the planting sites (MALEIEV, 1933). The planting of species introduced from abroad or from other sections of the same country is hazardous and must be carried on with rigid observance of the rules of acclimatization (MAYR, 1906; BÜHLER, 1922; CAJANDER, 1924; ILVESSALO, 1926; KERN, 1926*b*; ALBENSKY, 1933). The recent wholesale destruction of Norway spruce stands of central Europe by nun moth, spruce beetle, and red-rot has given most convincing evidence of the danger involved in the violation of the site requirements (NECHLEBA, 1923). While the danger of the introduction of "foreign" or "exotic" species is usually emphasized, often little consideration is given to the shifting of "native" species within the boundaries of a political unit, even though such a translocation sometimes involves greater changes in environmental conditions. A translocation of white spruce, for example, 200 miles from northern to southern Wisconsin may present a much more difficult problem of acclimatization than the translocation of Scotch pine from the Danube Valley, 5,000 miles, to central Wisconsin. Thus, a "foreign species", in a political sense, may be a "native species" in an ecological sense, and vice versa.

The first rule to follow in acclimatization is to confine the translocation of species as much as possible within the boundaries of the same natural soil-forest regions. Figure 31 presents a map of the principal soil-forest provinces of the United States.

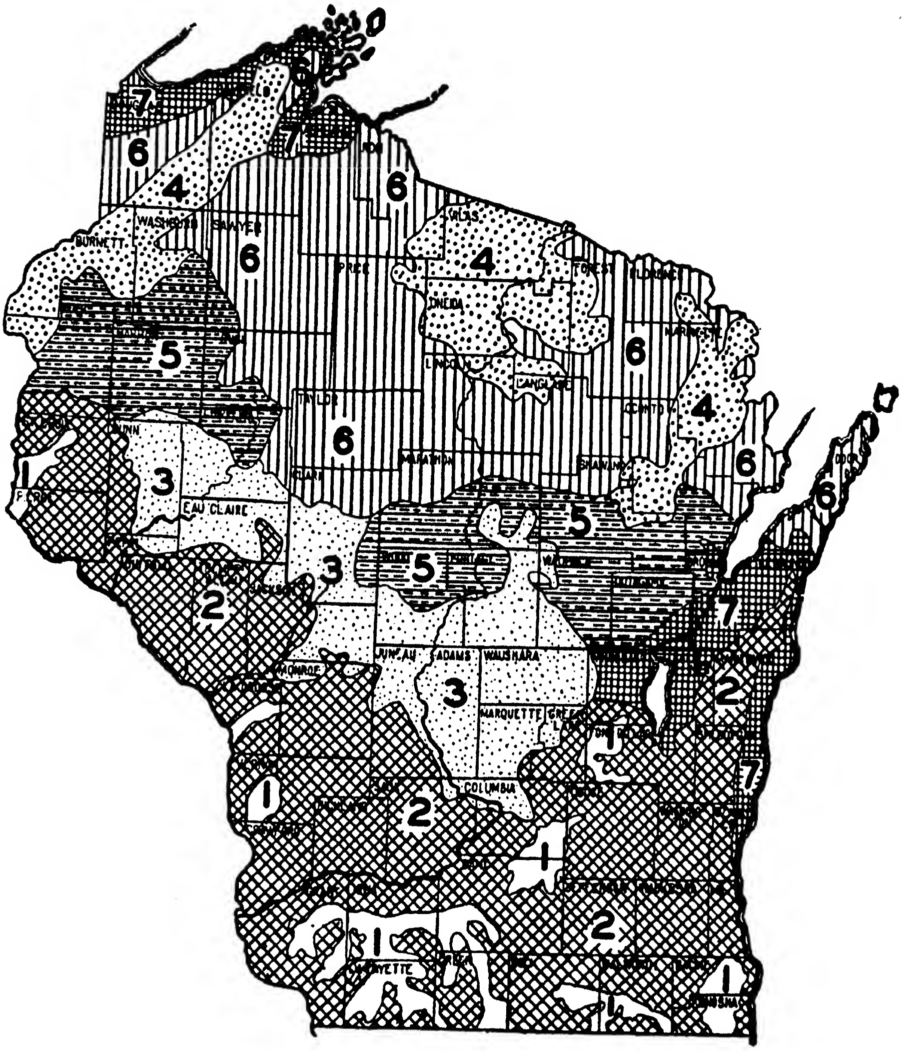


FIGURE 30. — Tree Planting Regions of Wisconsin: (1) *Prairie soils:* Tree planting is limited to shelterbelts, game-cover, and erosion control. (2) *Silt loams derived from limestones or calcareous drift:* White or green ash, American elm, hard maple, basswood, black walnut, hickory, and oak species; red and white cedar. Planting of other conifers is limited to smaller areas of strongly leached soils. (3) *Sands and sandy loams derived from siliceous rocks:* Jack pine, red pine and white pine; planting of deciduous species is confined to small areas underlain by clay substratum. The planting of spruce is inadvisable. (4) *Sands and sandy loams derived from granitic rocks:* Jack pine, red pine, white pine; planting of spruce is confined to the more favorable areas with boulder clay subsoil and accessible ground water. (5) *Slightly leached loam soils with mull humus:* Northern hardwoods; hard maple, basswood, American and rock elm, red oak; white pine. Planting of spruce is questionable. (6) *Strongly leached loam soils with raw humus:* Largely spruce and yellow birch; planting of maple, basswood and other northern hardwoods is confined to interspersed areas of slightly acid soils. (7) *Lacustrine clays:* White pine, white cedar, elm, hard maple, basswood; in the eastern portion also white ash and beech. Planting is often handicapped by the unfavorable physical properties of the soil, heaving, and high content of lime in the substratum, and should be carefully investigated in each individual case.

Selection of Planting Sites: — As a rule, the selection of planting sites on organized forest tracts constitutes a part of the forest soil survey which covers the entire management unit. Otherwise, areas suitable for planting of the available nursery stock are selected periodically according to the existing need. The sites for spring and fall planting are usually selected the preceding fall and summer, respectively.

The most important factors to be considered in the selection of planting sites are briefly summarized in the following outline:

(1) *Site factors:* — Exposure to sun and wind; distribution of precipitation, snow cover, winter killing, frost heaving, drought injury and sun scald. Danger of frost injury from the accumulation of cool air in frost pockets. Position of the area in regard to inundation. Effect of gradient upon soil erosion.

(2) *Soil factors:* — Height of the ground water table; saturation of soil in spring, effectiveness of capillary water in summer. Soil texture and structure; moisture content and aeration in critical periods, danger of frost heaving, possibility of leaving air pockets in the planting hole. Depth to impervious layers, such as hardpan, claypan, or rock substratum, and their effect on root development; danger of drought and windfall. Amount and type of humus; its effect upon the growth of plantations and possibilities of natural reproduction. Reaction of soil. Content of essential nutrients. Occurrence of layers high in carbonates, soluble salts, and toxic substances.

(3) *Biotic factors:* — Competition of herbaceous and woody vegetation. Danger of injury by rodents, game, and livestock. Possibilities of natural reforestation. Sociological relations of planted species to native vegetation including trees, shrubs, ground cover and lower plant forms. Danger of insect parasites and diseases.

TABLE 13. — *Planting Site Requirements of Some Representative Coniferous and Deciduous Species:* —

SPECIES TO BE PLANTED	Ability to survive on exposed cutover land	Minimum depth to ground water table	Minimum content of silt and clay particles	Minimum content of organic matter in 7-inch layer	Range of suitable reaction
		feet	per cent	per cent	*p*H
Red cedar	High	3.5	5	0.7	5.5-8.0
Longleaf pine	High	2.0	None	None	4.0-6.0
Red pine	Medium	3.5	10	1.8	5.0-6.5
White pine	Low	2.0	15	2.5	4.8-7.3
White Spruce....	Low	2.0	35	3.0	4.8-6.5
White cedar	Low	1.0	35	4.0	4.0-8.0
Black locust......	High	3.5	25	None	6.0-8.0
Cottonwood	High	1.0	10	1.8	5.5-8.0
White elm	Medium	2.0	25	2.5	5.5-8.0
Yellow birch	Medium	2.0	25	2.5	4.7-6.0
Hard Maple......	Low	3.5	35	3.0	5.5-7.3
Black walnut	Low	3.5	35	4.0	6.0-8.0

In addition to ecological conditions a number of purely economic factors, such as recreational value of the area, transportation facilities, danger of fire, etc., must be considered in the selection of planting sites.

Because the significance of soil factors varies considerably under different climatic conditions and with different ecological varieties of the same species, only general suggestions can be given in regard to the suitability of soils for planting various trees. Table 13 presents approximate data on the depth to ground water level, soil texture, content of organic matter, and reaction of soil related to the planting of several silviculturally important coniferous and hardwood species. It should be stressed that success in planting cannot be assured with species having only medium or low ability to survive on exposed cut-over areas unless such species are planted

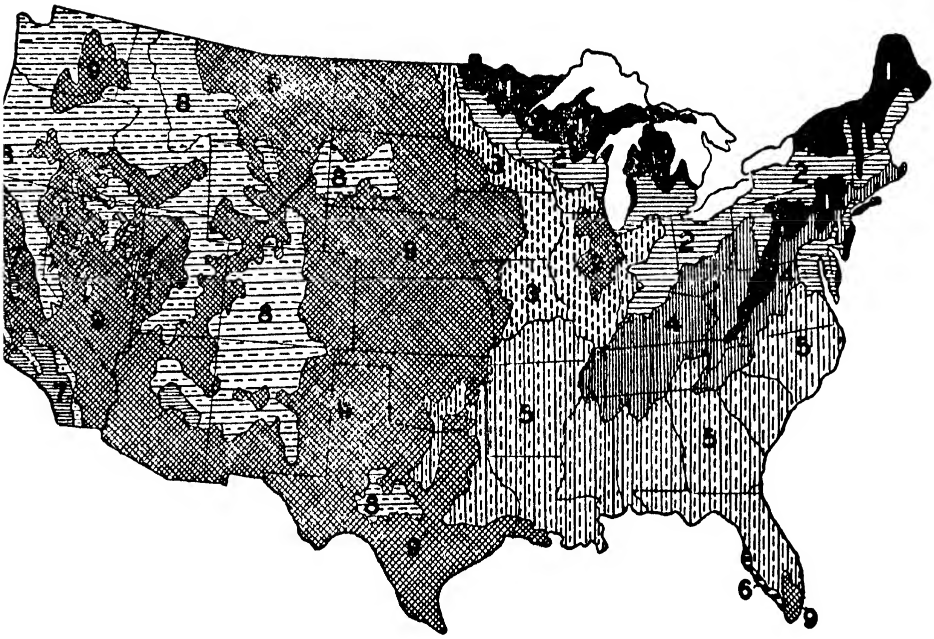


FIGURE 31. — Soil-Forest Provinces of the United States.

1. *Podzols.* — *Northern Coniferous Forest* (Spruce, fir, hemlock, yellow birch).
2. *Podzolic Soils.* — *Mixed Hardwood-Coniferous Forest* (White pine, hemlock, hard maple, basswood, beech).
3. *Grood Soils.* — *Prairie Forest* (Oaks, hickory).
4. *Melanized Soils.* — *Central Hardwood Forest* (Chestnut, chestnut oak, tulip poplar, beech, hard maple).
5. *Podzolized and Melanized Lateritic Soils.* — *Southern Pine and Hardwood Forest* (Longleaf pine, shortleaf pine, loblolly pine, slash pine, cypress, oaks, gums, magnolia).
6. *Mangrove Swamps.* — *Subtropical Forest* (Mangrove).
7. *Charral Soils.* — *Sclerophyllous Forest* (Evergreen oaks, manzanita, wild lilac with some pines and junipers).
8. *Mountain Soils.* — (Undifferentiated) — *Western Coniferous Forests;*
   (a) Weakly developed mountain soils — piñon, juniper, pondersosa pine, Douglas fir;
   (b) Mountain podzolic soils — Western white pine, western red cedar, western hemlock;
   (c) Mountain podzols — Spruce, fir, larch;
   (d) Sod soils — Subalpine forest.
9. *Non-Forest Soils.* — *Grasslands and Deserts.*

under the protection of a nurse stand (Stoeckeler and Limstrom, 1942). The stated minimum contents of silt and clay particles may be somewhat high for planting on soils with a high ground water table, or in regions influenced by large bodies of water. However, even under such conditions it is not advisable to lower the standards without urgent need, as the content of colloids is related not only to the water-holding capacity of soil but also to the content of available nutrients. It is important in the selection of planting sites to keep in mind that the species planted should not only *survive* on the selected site, but also *produce high yields of timber* justifying the planting cost.

Ordinarily, the content of available nutrients is correlated with the content of soil colloids, organic matter, and the *p*H value of soil. In the majority of cases, therefore, a detailed chemical analysis of soil can be omitted in the selection of planting sites. In a broad way, chemical composition and the potential fertility of soils, not greatly altered by the processes of podzolization or laterization, may be estimated on the basis of the origin of the parent soil material as outlined in Table 14.

Table 14. — *Relation of Geological Origin of Soils to Their Potential Productivity and Planting Possibilities:* —

Nature of parent soil material	Probable chemical composition of soil or substratum	Reforestation possibilities
Siliceous Rocks Sandstone Quartzite Siliceous shales	Low content of nutrients, especially phosphate and potash	Pines and less exacting deciduous pioneer species
Acidic Rocks Granite Syenite Gneiss	Adequate content of nutrients with possible exception of lime	Conifers and hardwoods with the exception of pronounced lime-demanding species
Ferro-Magnesian Rocks Diorite Diabase Basalt	High content of nutrients, especially calcium and magnesium	Hardwoods; conifers, particularly spruce, tend to produce high yields but are often subject to fungous diseases
Calcareous Rocks Limestone Dolomite Calcareous shales	High content of lime; possible deficiency of phosphate and potash	Lime-tolerant hardwoods and conifers *viz.*, oaks, hickory, walnut, ash, beech, red and white cedar, Austrian pine. Planting of the majority of conifers is questionable

In order to ascertain the presence of an adequate supply of essential nutrients in soils to be reforested, it may be desirable in some instances to analyze representative soil samples in the laboratory. Such analyses are particularly desirable in regions showing poor growth of native stands or plantation. As a rule, the analysis can be limited to the upper 7-inch layer of soils as its composition usually reflects the properties of the substratum and is of decisive importance in the initial growth of planted trees. In some instances, however, it may be necessary to analyze the lower soil layers provided they occur at a depth which can be reached by the roots of seedlings within a few years. The roots of cottonwood or some other deciduous species may reach a fertile substratum lying as deep as 6 or 7 feet during the second growing season after planting. The available data on the minimum fertility levels necessary for a satisfactory growth of different groups of trees are given in Table 15. The contents of nutrients required by trees in forest plantations are very low in comparison with agricultural or forest nursery standards. This is because trees in plantations derive their nutrients from a much greater volume of soil than do field crops or nursery stock. For this reason, the deficiency of nutrients in reforestation practice is exceptional and is

confined chiefly to soils derived from purely siliceous and calcareous rocks, or soils depleted by repeated burning and cultivation (WILDE, TRENK, and ALBERT, 1942).

TABLE 15. — *Minimum Contents of Essential Nutrients Necessary for a Satisfactory Growth of Representative Tree Species in Plantations:* —

TREE SPECIES PLANTED AT A SPACING 4 BY 4 FEET OR GREATER	Content of Nutrients in the upper 7-inch layer of soil				
	Total N	Avail. P_2O_5	Avail. K_2O	Repl. Ca	Repl. Mg
	%	lbs./acre		m.e./100 gms.	
Pioneer pines, such as longleaf pine, jack pine and Scotch pine	.02	Tr.	30	.4	.1
Intolerant coniferous and deciduous spp., viz., larch, red pine, wh. pine, birch and alder	.05	20	50	1.5	.3
Tolerant conifers and northern hardwoods—e.g., spruce, fir, hard maple, basswood	.10	50	125	2.5	.7
Lime-demanding hardwoods; e.g., white ash, black walnut and hickory	.10	50	150	4.5	1.2

The composition of the ground cover vegetation, if correctly interpreted, furnishes valuable information in regard to the selection of suitable species in planting or silvicultural cuttings (CAJANDER, 1909; CLEMENTS, 1920; KRUEDENER, 1934*b;* COILE, 1938). Table 16 presents an example of a floristic classification related to the reforestation possibilities in the area of recent glacial drift of northern Wisconsin (WILDE, 1933). As a general

TABLE 16. — *Ground Cover Vegetation as an Indicator of Reforestation Possibilities in Northern Wisconsin:* —

TYPE OF GROUND COVER AND SOIL	Outstanding members of ground cover association	Species to be planted or encouraged in selective and release cuttings
Cladonia-'Nudum' (Barren sand)	Reindeer moss, related lichens, xerophytic mosses and grasses	Reforestation is limited to control of wind erosion
Arctostaphylos-Ceanothus (Humus-incorporated sand)	Bearberry, New Jersey tea, low blueberry, dwarf hazel and willow	Jack pine; red pine on more favorable areas. The site is well suited to artificial reforestation
Gaultheria-Maianthemum (Leached sand or light sandy loam)	Wintergreen, Canada mayflower, blueberries, shin leaf, trailing arbutus, sweet fern, hazel, and blackberry	Red pine; white pine on more favorable protected areas. Natural reproduction is easily obtainable
Vaccinium-Cornus (Sandy podzol)	Large blueberry, bunch berry, wintergreen, bracken fern, partridge berry, twin flower, dew berry, bush honeysuckle	Natural reproduction is likely to be more successful than planting; the latter is often handicapped by the occurrence of ortstein or gley layers. White pine on more favorable areas
Adiantum-Osmorhiza-Thalictrum (Humus-incorporated loam)	Maidenhair fern, sweet Cicely, meadow rue, Dutchman's breeches, blue cohosh, trillium, waterleaf, green briar, leatherwood, arrowwood; numerous shrubs	Reforestation is confined to rough and stony areas because of the high agricultural value of land. Natural reprodction is very vigorous. Hard maple, basswood, other hardwoods; spruce
Smilacina-Polygonatum (Leached loam)	False and true Solomon's seal, Canada mayflower, twisted stalk, bellwort, trillium, sarsaparilla	Spruce; yellow birch and elm. This site is well suited to artificial reforestation
Clintonia-Lycopodium (Loam podzol)	Clintonia, club mosses, partridge berry, gold thread, bunchberry, twin flower, mosses and ferns; no shrubs	Planting is often handicapped by the occurrence of ortstein or gley layers and natural reproduction of hemlock, fir, spruce and hardwoods should be given preference whenever possible

rule, floristic classifications have only local significance and should be modified on the basis of a careful study of conditions as they occur within a given region (Plate 5).

Methods of Planting: — In many cases the selection of the proper method of planting is just as important as the selection of the species to be planted. The following discussion outlines the main features of the common planting methods (Figure 32) and reviews their adaptation to different soils and sites (DENGLER, 1930; TOUMEY and KORSTIAN, 1931).

(1) *Slit planting:* — A slit about 10 inches deep is made by means of a planting bar; the roots of the seedling are placed in the slit, and the slit is closed by another thrust of the bar and the planter's heel. In this type of planting the roots are forced during the first season to feed and absorb water in one vertical plane. Long roots must be trimmed to a length corresponding to the depth of the slits and in gravelly soils which resist the penetration of the planting bar the root system is usually reduced beyond reasonable limits. In heavy soils air pockets are often left in closed slits and the roots are exposed to drought. Satisfactory results with this method, therefore, may be obtained only on stone-free sandy soils; on such soils slit planting is the cheapest method and compares very favorably with elaborate hole planting (WILDE and ALBERT, 1942).

In the reforestation of mountain soils slit planting is preferably accomplished by the use of a grub hoe; in general, however, this tool is more laborious than the planting bar. Sometimes the planting bar is replaced by a spade which is used to remove a wedge-shaped portion of soil. The roots of the seedlings then are spread against the vertical side of the hole and the wedge of soil is placed in its original position and thoroughly tamped with the foot. This modification of slit planting reduces the danger of leaving air pockets and may be applicable to soils of fairly heavy texture.

(2) *Hole planting:* — The mattock, grub hoe, shovel or spade are used to dig a hole slightly larger than the extension of the seedling roots. The seedling is held in position with the roots well distributed in the hole. The top soil is then placed about the roots and thoroughly packed with the foot. Hole planting enables the seedlings to utilize larger quantities of moisture and nutrients in the earlier stages of growth, and is considered to be one of the most reliable methods (DENGLER, 1930). It is adapted to a wide range of soils, including those of stony or gravelly nature; strongly leached cemented podzol soils, very shallow residual soils, and soils with a high ground water table are exceptions. Hole planting allows the mixing of additional fertile soil or the use of other fertilizing materials if such are to be applied.

(3) *Mound planting:* — The sod layer is removed with a spade or mattock and a mound is made from surface soil collected nearby. The seedling is planted by hand with the roots spread as much as possible. Sometimes the mounds are prepared a year or more in advance of planting, and a dibble or a spade is used to make the hole for the seedlings. A special planting iron devised by HENNING is also used to impress a hole in the mound. This iron makes three slit-like holes extending radially downward so that the roots may be spread laterally in their natural position and covered with fertile soil.

Mound planting is of greatest importance in reforesting poorly drained soils where the mounds insure a fair degree of soil aeration for young seedlings and reduce frost heaving. Mounds are sometimes used on heavier, upland soils in order to place the seedlings in an elevated position and thus give them a better opportunity to compete with weed vegetation. This method may be necessary in planting shallow residual soils, particularly those derived from calcareous rocks. It is advantageous on podzol soils underlain by a hardpan horizon. On soils of a light sandy texture wind erosion is apt to destroy the mounds and expose the root system. MANTEUFFEL (1874), and later SIGMOND (1924) advocated mound planting as a means of increasing survival of plantations in times of drought.

(4) *Planting in furrows:* — Furrows for tree planting are made with a special plow and tractor. The depth of furrows is varied according to site requirements from 3 to 12 inches. The planting itself is accomplished by means of mattock, spade, or spud.

The chief advantages of furrowing are: (*a*) the plow and tractor destroy the grass, brush, and other competing vegetation; (*b*) when furrows follow contour lines they retain some run-off water and may thus provide a greater amount of moisture for the seedlings; (*c*) the plowing may help the seedlings to reach the capillary water in a shorter time; (*d*) on exposed sites, deep furrows protect the seedlings from wind and sun. The most serious disadvantages of furrowing are: (*a*) The plow removes the surface humus layer of the soil thereby decreasing the water holding capacity and content of nutrients; (*b*) on heavier soils and in regions subject to early or late frosts, the water accumulated in the furrows may cause frost heaving; (*c*) plowing may expose toxic or impervious layers, such as hardpan, claypan, calcareous layers or unweathered rock substratum.

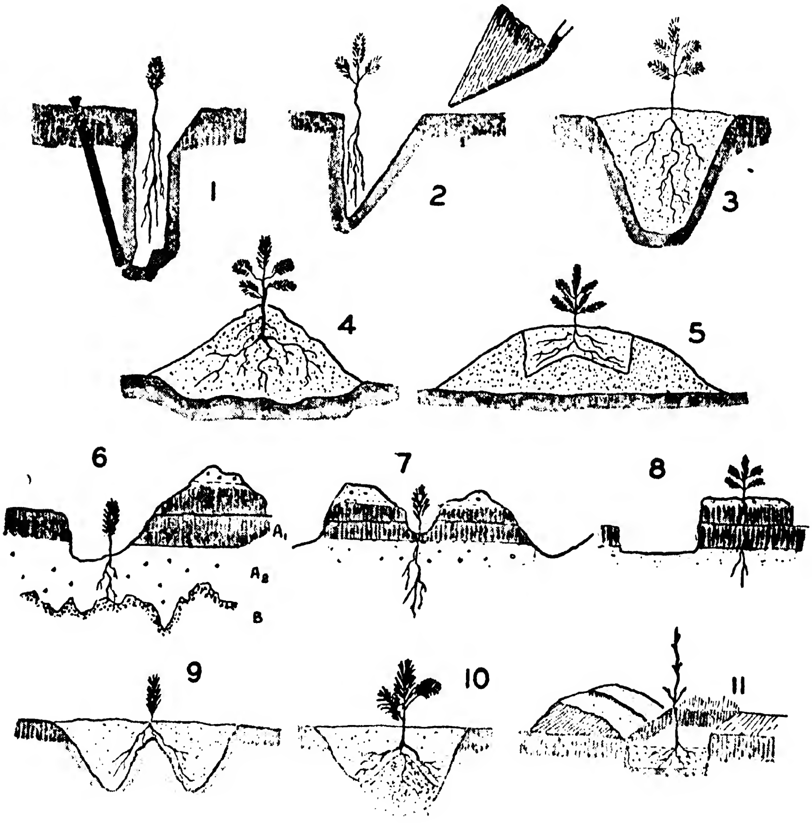


FIGURE 32. — Methods of tree planting. 1. Slit planting; 2. Spade planting; 3. Hole planting; 4. Mound planting; 5. Mound planting using Henning's tool; 6. Furrow planting; 7. Double furrow planting; 8. Planting on turned sod; 9. Inverted V planting; 10. Cone planting; 11. Sod cover planting.

Experience has shown that deep furrowing is particularly beneficial in increasing the survival of seedlings on extensive cut-over areas exposed to the desiccating effect of wind and sun (WILDE and ALBERT, 1942). On sandy soils this increased survival is obtained at the cost of a somewhat lower rate of growth of the plantation during its earlier stage of development. Shallow plowing is beneficial chiefly on heavy mull soils where it destroys the abundant competing vegetation but leaves a part of the humus layer undisturbed. Planting in furrows is impracticable on podzols and shallow residual soils. Also this method is not feasible on stony soils and areas sup-

porting heavy sprouts. On such areas furrowing should be replaced by scalping. It is important to orient the furrows in such a manner as to provide maximum protection of planted seedlings from both the sun and the prevailing desiccating winds. On soils supporting a heavy cover of strong, fast-growing grasses, a narrow V-shaped furrow is made with a special four inch scooter plow. Two broad furrows are turned inward at a distance of about two feet on each side of the scooter furrow. The scooter furrow thus forms a catch basin for rainwater and checks the growth of competing grass.

(5) *Planting on turned sod:* —The seedlings are set on the furrow slice or on the turned-back sod of scalped spots. The purpose of this method is to secure the nutrients and moisture of a double humus layer, to place seedlings in a higher position so as to reduce the competition of herbaceous vegetation, and to provide better aeration on wet sites. Plowing or scalping is done in the fall preceding the spring planting or even earlier in order that the furrow slice or sod layer may settle and produce a uniform solid medium for planting. Seedlings are planted with the planting bar or spud.

This method is applicable chiefly in underplanting or in reforestation of small protected cut-over areas. On exposed sites the trees are often destroyed by drought and sun scald. Planting on turned sod is sometimes used in reforestation of podzol areas underlain by an ortstein horizon. In such plantings, the ridge is often made by turning two furrows inward. Similar technique is employed in planting wet soils.

(6) *Cone planting:* — The planting hole is dug with a spade or grub hoe. A conical mound is made in the bottom of this hole using some of the best soils, and the roots of the seedling are spread over its surface with the hand. More of the best soil is then placed over the roots and packed with the hands. Finally all the remaining soil is added and thoroughly packed. This method of planting provides a greater surface area for contact of the roots with the soil and is suitable to any deep, well drained soil. It is primarily adapted for planting shallow rooted species, but not trees with a single tap-root.

The same objectives are reached by the so-called inverted "V" method in which the hole is dug with two separate downward strokes of a *Baldwin* planting hoe or a mattock in such a manner that an inverted V-shaped ridge or saddle of soil is left across the hole.

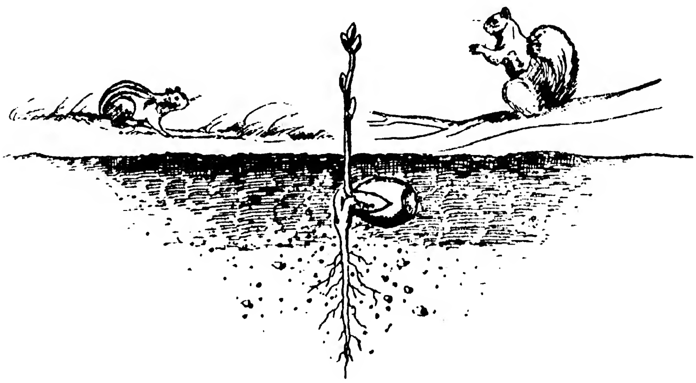
(7) *Sod cover planting:* — A block of sod about one foot square is cut loose on three sides with the spade and turned back. The seedling is planted in the exposed soil. The sod layer is then cut through the middle and folded back into its original position. The depth of planting is regulated by the thickness of the sod layer, so that the seedling is not buried too deep. This method, introduced by ALEMANN, is used on heavy soils subject to frost heaving, especially in planting large sized stock of deciduous species such as alder, birch and ash.

Diagnosis of the Conditions Responsible for the Failure or Stagnation of Plantations: — Unsatisfactory growth of planted trees may be caused by a number of factors including adverse conditions of soil and climate, destructive biotic agents, inferior quality of planting stock, or defective planting technique (KOBRANOFF, 1930; RUDOLPH, 1939). Among the properties of soil the following are of primary importance as causes of stand deterioration; inadequate content of colloids and the resulting deficiency of soil moisture; high ground water table or excessive content of moisture and consequent insufficient aeration; unsatisfactory soil structure due to a high content of clay, cementation by translocated colloids, packing by livestock, and cracking or heaving of soils; deficiency of humus; unsuitable reaction, lack of certain essential nutrients, or presence of toxic substances. On many occasions the unfavorable properties of the soil are amplified by inadequate scalping, too deep plowing, or careless planting.

In some instances the trees are damaged by inundation, water or wind erosion, toxic industrial fumes, grazing, competition of grass vegetation,

rodents, insect pests, or parasitic fungi. The deterioration of direct seedings may be caused by lack of mycorrhizal fungi.

If no primary adverse factor is revealed in field examination, information must be obtained on the state of climatic conditions during the preceding few years, especially on the occurrence of dry spells, winter killing, early fall and late spring frosts, strong evaporating winds, and temperatures high enough to cause sunscald. These data should be supplemented by a careful investigation of the origin of planting stock, particularly the source of seed, and climatic conditions of the region where the nursery is located. In addition, information should be secured on the content and balance of nutrients in the nursery soil, its *pH* value, the method of watering, shading, fertilization, lifting, and control of parasites, especially the use of toxic fungicides and insecticides. In doubtful cases the advice of a plant pathologist or entomologist is highly desirable. The soil should be subjected to detailed analysis in the laboratory provided careful preliminary investigation has reasonably eliminated the possibility of non-edaphic causes of injury or deterioration. No conclusions should be reported unless they are based on positive evidence.



Chapter XIII

AMELIORATION OF FOREST SOILS

Utilization of Run-off Water: — In regions with undulating or rolling topography, the rate of forest growth may be materially increased by interception and careful distribution of run-off water. This is accomplished by a network of shallow ditches or plowed furrows. The furrows are laid out perpendicularly to the main drainage channels with a gradient not exceeding 1 per cent. If the soil is easily eroded, the allowable gradient is even lower (WANG, 1903). The water from the drainage channels, as well as from higher portions of the slope, is diverted from its course by furrows and is gradually absorbed by the soil. Simple dams of cull logs or poles are constructed in the main drainage channels to facilitate the diversion of water into the furrows. The system of intercepting ditches may conserve as much as 30 per cent of the total precipitation which is ordinarily lost in the form of surface run-off. Work of this kind presents a useful outlet for employment of permanent forest labor in slack seasons.

The damming of streams for the creation of artificial water basins leads to a general rise of the ground water level. In regions of plains or terraces this may bring the ground water to a suitable height and thus benefit the growth of forest stands on a considerable area. Such improvement of upland soils, however, may be partly or wholly offset by a simultaneous deterioration of the lowland soils that are located within the influence of the backwater.

Drainage of Wet Lands: — The artificial lowering of a high ground water table may be, under certain circumstances, a feasible means of stimulating forest growth. The drainage of small areas underlain by a thin impervious layer can be improved by dynamiting or digging holes which facilitate the "sinking" of the excessive water. A special auger with extensions is advantageously employed for this purpose. In some cases it may be necessary to install a vertical tile which comes within 3 feet of the ground surface. Stream improvement work for accelerating the current, especially the removal of beaver dams, may materially decrease the stagnation in backwater swamps and marshes. Frequently a short outlet ditch is sufficient to penetrate a barrier which is responsible for the retention of run-off water. The drainage of ravines choked with fallen logs may be easily accelerated by merely clearing the rubbish from the surface. Inexpensive intercepting ditches may be installed to keep the surface and seepage water from entering potholes. By these methods the amelioration of impeded drainage may be accomplished with very little expense. As a rule, minor drainage improvements are confined to areas supporting stands or plantations of valuable species and are carried on by permanent forest labor during slack work periods.

The drainage of large areas, particularly swamps, requires thorough investigation of a number of conditions previous to the initiation of the drainage project proper. Among these conditions, the following are of prime importance: (*a*) potential productivity of soil or peat; (*b*) practi-

cability and efficiency of proposed drainage system; (*c*) expected financial return on the investment; (*d*) effect of drainage and subsequent lowering of ground water table upon the productivity of surrounding upland stands; (*e*) effect of drainage upon the entire water regime of the region, and especially its effect upon agriculture. In climates where drought presents a serious problem, the two latter conditions usually make extensive drainage projects inadvisable (KAUTZ, 1912; ZON, 1927; LUKKALA, 1928; ZON and AVERELL, 1928; MALMSTROM, 1928; WISSOTZKY, 1938).

The drainage project involves a thorough study of the subsoil condition and outlet possibilities. The depth and permeability of the subsoil are examined by means of an auger or post-hole digger. The outlet is investigated with surveying instruments. The leveling should be continued some distance below the proposed outlet to make certain there is no danger of backwater. Specific literature on the subject and a technician experienced in drainage work should be consulted whenever an extensive project is contemplated (LUNDBERG, 1926; LUZE, 1927; LIVINGSTON and WACKERMAN, 1927; ROE, 1928; EDIN, 1928; BURGER, 1937; AYRES and SCOATES, 1939).

The drainage of wet forested land, as a rule, is accomplished by open ditches and rarely by drain tile. The main objection to the installation of tile is the tendency of tree roots to plug the pipes. If the area has no outlet, excess of water may be removed by means of a so-called "Swedish drain". This consists of a continuous storage ditch which surrounds the basin area and intercepts the water from the higher portions of topography. The general aim of drainage for forestry purposes is to speed up the flow of the ground water rather than to attain a "bone dry" condition (AVERELL and McGREW, 1929).

Because of high cost, tree planting on peat lands is limited to rare cases. A reasonable assurance of success often requires an elaborate afforestation procedure. After the drained peat has settled to about two-thirds of its original volume, and an invasion of grasses and sedges is evident, the soil from the drainage ditches is spread on the surface of the peat, and the area is burned. The fire is set on the windward side so that it will move rapidly and not penetrate deeply. The burned-over area is then kept in buckwheat for about 5 years. In the fall of the sixth year the peat is disked, burned once more, and in the spring is planted to trees. Depending on the condition of ground water level, the seedlings are planted in slits, or on top of the ridge formed by two furrows turned inward. Sometimes the surface layer of peat is removed by steam shovel before reforestation, and used as fuel or fertilizer material (MULTAMÄKI, 1920; SPRINGER, 1925).

Stabilization of Blow Sands: — The stabilization of sand dunes was one of the earliest activities of foresters in both the Old and New Worlds. In Central European countries the first stabilization attempts date back to the middle of the eighteenth century (GEHRHART, 1900), while dune fixation at Cape Cod was initiated in 1826 (BACKER, 1906). A vivid description of the destructive effect of wind erosion has recently been given by KROODSMA (1937). In his words, "To a person unfamiliar with moving sand dunes, it is hard to realize their magnitude or the grim wave-like action with which they advance, burying everything in their path. Examples

of their destructive action are numerous. Old geographies of Michigan show that a once thriving sawmill town was located at the mouth of the Kalamazoo River near the present town of Saugatuck. Singapore was completely buried by a sand wave and became known as the Pompeii of America . . . . In other sections of the state, highways are being covered, harbors are filling up and resort cottages are threatened with burial."

In only a very few instances can the movement of sand dunes be arrested by direct planting of forest trees. As a rule, the blow sands must be at least partly stabilized prior to planting. This may be accomplished by means of wooden stakes which are cut to an approximate length of 20 inches and driven into the ground to a depth of 8 inches thus forming a series of fences. The fences are arranged in parallel rows or in the form of squares or rhomboids. The distance between the rows varies with the intensity of erosion and is determined on the basis of experience. The determination of the proper distance between the rows is of extreme importance as its regulates the efficiency and cost of control (HEUSOHN, 1929). The spreading of slash, cornstalks, hay, reeds or any other suitable materials on the windward side may replace the expensive construction of fences. The planting of xerophytic grasses in clumps or sowing of rye is another method of sand stabilization. *Elymus arenarius* and *Ammophila arenaria,* are the grass species commonly used. The latter is particularly favored in the United States (LEHOTSKY, 1941).

After the sand movement is arrested, the dunes are planted to jack pine, scrub pine, pitch pine, Scotch pine, Austrian pine, western yellow pine; mugho pine, maritime pine, Russian willow, cottonwood, or black locust. In exceptionally humid regions, along the shores of the sea or large lakes, more exacting species, such as white pine, red pine, birch, white poplar, and European grey alder are also planted in the depressions between the dunes (GREELEY, 1920; MONROY, 1921; BUFFAULT, 1936; TRENK, 1938). As a rule, conifers prove to be superior to deciduous trees. Experience has shown that the control of sand movement is best achieved by a combination of several control measures, such as spreading of brush, tree planting and seeding of grass.

Reclamation of Hardpan Soils: — The extensive areas of hardpan podzols, or "Heide", supporting low shrubs of the heather family, are ameliorated by deep cultivation, using a steam plow. The cultivation is often preceded by burning the vegetative cover. The land is plowed to an approximate depth of 18 inches or deeper and the plowing is repeated in crosswise manner until the hardpan material, leached soil and raw humus are thoroughly mixed. Sometimes the hardpan layer is destroyed by dynamiting instead of plowing. As a rule, lime or marl is added to decrease the acidity of soil, speed up nitrification, and convert into available form the nutrients concentrated in the ortstein layer. After cultivation, the land is fallowed for one or two years, or is seeded to green manure crops, particularly to lupine (LORENZ, 1908; RAMANN, 1911; MEINECKE, 1927; WEIS, 1929). The technique of ortstein soil reclamation was originated largely in northern Germany, Jutland and Holland.

Pine and spruce are the chief species used for reforestation, the choice being dependent upon the texture of soil and other conditions. White

birch, aspen, oak, blue beech, mugho pine and larch are planted along with spruce and pine for the purpose of soil improvement. American red maple, which grows naturally on podzol soils, may be of great value as an associate species in this type of reforestation. The seedlings are usually planted on the top of the ridge formed by two inward-turned furrow slices.

Before the amelioration of an ortstein podzol is attempted, the composition of the soil profile should be carefully investigated over the entire area. Since the depth of the ortstein layer varies considerably from place to place, there may be many areas which have a sufficiently deep leached layer to allow direct planting. Plowing is likely to be most advantageous on areas with a shallow and thin ortstein layer which may be completely destroyed by the plow. As experience of the U. S. Forest Service in the Lake States region has shown, the furrowing of thin hardpan soils results in the increased growth of planted seedlings due to the benefit of the additional nutrients from the disintegrated ortstein material. In places neither direct planting nor plowing are practicable and the area should be left to natural reproduction.

The amelioration of forested hardpan soils is carried on over a long period of time by means of partial cuttings which discourage the accumulation of raw humus, and by under-seeding or under-planting with soil-improving hardwood species (Emeis, 1875; Wiedemann, 1923; Sigmond, 1924; Mařan, 1938).

Reclamation of Rock Barrens: — The processes of erosion in places remove the entire mantle of weathered fine-earth and thus expose the bedrock. This is especially common in regions of calcareous formations, as exemplified by the ill-famed Karst Mountains (Leiningen, 1931). Restoration of vegetative cover on such denuded areas is one of the most difficult tasks of land amelioration. Yet, many astonishing conversions of rock debris and talus slopes into fairly productive forest tracts have been accomplished by foresters of Austria, France, and other countries of central and southern Europe (Wang, 1903; Púcich, 1907; Stiny, 1908; Thiery, 1915; Kaisler, 1921).

On many occasions, the afforestation of rock barrens is achieved by filling fissures or crevices with soil transported from nearby valleys or depressions. Sometimes trenches must be excavated in the rocks to receive the soil and seedlings. As a rule, only strong transplants are used in afforestation of such sites. The cost of planting may be as high as $60 per acre. Under American conditions, this expense may be justified only in cases where rock falls threaten lines of communication.

Afforestation is usually initiated with Austrian pine, other pines, larch, red cedar, black locust, European grey alder, and other pioneer species of trees and shrubs (Schneider, 1924; Leiningen, 1931; Dengler, 1931). In planting on calcareous rocks, the selection must be limited to species tolerating alkaline reaction and a high content of carbonates (Turner, 1933). In time, the pioneer plantations may be reenforced by the underplanting or under-seeding of hardwoods having powerful root systems.

Control of Gullies: — Gullies are the end result of various forms of land abuse. In the early stages, the destructive effects of run-off may be

arrested by limited reforestation, simple dams of culled logs, and similar inexpensive measures. The progress of gully erosion proceeds at an extremely rapid rate, and in the course of a few years its control may present a serious problem for both foresters and engineers.

The choice of species used in planting gullies and surrounding territory is governed chiefly by their ability to control erosion. Each gully includes three sets of ecological conditions: bottom, which periodically receives a considerable quantity of run-off water; eroded banks with "raw", humusless soil; bordering slopes with a normal soil profile, undisturbed by erosion (KERN, 1926*a*).

The banks and the drier bottoms are planted to black locust or other drought resistant trees with moderate nutrient requirements and a fibrous, soil-binding root system. In the planting of wet gully bottoms, heavy rooted, moisture-loving trees such as cottonwood and willows are used. The bordering strips are planted to a variety of trees and shrubs, *viz.* Russian olive, buffaloberry, Siberian pea tree, Staghorn sumac, Russian mulberry, osage orange, privet, thornapple, thornless honey locust, highbush cranberry, nannyberry, common lilac and wild plum. The selection of species depends upon the soil reaction, moisture condition, and other factors. On suitable soils spruce, pine and cedars are mixed with deciduous species in order to provide game cover in winter.

Because of the low fertility of the eroded portion and the heavy sod on the undisturbed slopes bordering the gully, only large and vigorous stock is used. The spacing varies from 2 by 2 to 3 by 3 feet. In some instances, forest planting is supplemented by the seeding of eroded banks to timothy, rye, blueglass and clover or by the laying of sod on more exposed sections. Extensive gullies in an acute state of erosion may require engineering work prior to reforestation (BENNETT, 1939).

Afforestation of Prairie Soils: — The first efforts to afforest prairie lands were based on the assumption that planted forests will increase the amount of rainfall and thus will benefit the climate in the entire region (MIROV, 1935). Although these ideas have been recently proven unfounded, there are a number of other reasons which well justify "prairie forestry". In no other region have shelterbelts, windbreaks, or farm woodlots such value as in vast exposed grasslands; plantations of this kind produce tremendous improvements in the environment of dwellings, protect stock and game, and provide fuel or small-dimension wood for general use.

Climatic conditions of the prairie region are characterized by low annual precipitation, summer drought, great temperature extremes, and frequent strong winds. The soils of the region include chernozems, chestnut soils, alkali soils, and areas of dune sands. The comparatively suitable areas for tree planting in this forest-hostile environmental complex are confined to slopes which collect snow drifts and thus insure a higher content of soil moisture. On such sites the perlocating water lowers the zone of lime enrichment and decreases the concentration of soluble salts. Alkali soils of depressions having a high concentration of soluble salts and soils with a zone of lime enrichment or hardpan layer close to the surface should be avoided in tree planting as much as possible (WISSOTZKY, 1930; SCHOLZ, 1935).

The afforestation of prairie is often initiated by the planting, in suitable localities, of shrubs and dwarf trees which help to accumulate snowdrifts and thus tend to promote the process of soil podzolization. After leaching has decreased the *p*H value of the surface soil, and lowered the zone of lime enrichment, the area may be planted to tree species with greater success (WISSOTZKY, 1930; BUCHHOLZ, 1930).

As a general rule, the survival and growth of trees in the prairie region increases with the sand content and decreases with the clay content of the soil. This is chiefly due to the higher content of available water in sandy soils. The content of available water in heavy soils is low because of slow absorption rate, rapid run-off, retention of light precipitation in the upper soil layer and a high wilting coefficient. Large cracks developing in heavy soils during drought periods may also handicap tree planting (STOECKELER and BATES, 1939).

The tree species which have proven most successful for prairie planting are: green ash, hackberry, American elm, Chinese elm, bur oak, black locust, honey locust, catalpa, osage orange, willows, cottonwood, western yellow pine, Austrian pine, Colorado blue spruce, junipers and eastern red cedar. The shrub species commonly used include Russian olive, buffaloberry, chokecherry, Siberian pea tree, serviceberry, hawthorn, Russian mulberry, Tartarian honeysuckle, nannyberry and lilac (SILCOX et al., 1935).

Recent evidence indicates that the presence of mycorrhizae on the roots of planted stock, or an inoculation of seed with mycorrhizae-containing media, is essential in the afforestation of prairie soils (HATCH, 1936; MCCOMB, 1938; BARANEY, 1939; WHITE, 1941; ROSENDAHL, 1943).

The areas to be planted are often fallowed to reduce the competition of grasses and increase the content of soil moisture. In some instances, the planted areas are periodically cultivated for the same purpose.

Use of Field Crops in Reforestation: — In some instances satisfactory results in reforestation of worn out fields were obtained by raising lupine and other leguminous green manure crops previous to tree planting. For this purpose the soil is fertilized broadcast with phosphate and potash. The green manure crop is seeded in the spring and plowed under the next fall. The following spring the soil is disked and harrowed and seeded or planted to tree species. Sometimes, the plowing under of the green manure crop is omitted in order to lower expenses or to reduce wind erosion (WIEDEMANN, 1927; SÜCHTING, 1928; HELLWIG, 1934).

On soils having a fairly high content of nutrients, cover crops, chiefly rye and oats, are seeded sparingly simultaneously with the tree planting. In the fall the cover crop is cut high with a scythe or mowing machine. Such a practice reduces weeds and provides some protection to seedlings during the first growing season. The harvested grain may help to defray the cost of planting. Potatoes and corn are raised between rows of planted trees for the same purpose. Such combined use of the land, however, is often detrimental to forest plantations, especially on soils poor in nutrients or soils with unstable structure (HAUSRATH, 1911; REBEL, 1924).

Cultivation of Forest Stands: — The stagnant growth of plantations, caused by the competition of weeds or sod vegetation, can be materially improved by cultivation. In reforestation of Wisconsin sandy podzols, repeated disking has increased the average height of jack pine on some areas from 3.9 feet to 11.2 feet in the course of nine years.

Cultivation is accomplished by means of a one-horse cultivator, special Neumann forest cultivator, disk, or rototiller. Great care must be exercised in cultivation to avoid injuring the tree roots. On soils deficient in humus, cultivation is likely to have detrimental results as it promotes the decomposition of organic matter and subsequent leaching of nutrients (NĚMEC and MAŘAN, 1936-1938; NĚMEC and BORISOV, 1938). Cultivation may also affect adversely the porosity and aeration of the surface soil; this, however, seldom is as serious as suggested by BURGER (1922).

Harrowing or raking is sometimes practiced on raw humus soils to stimulate natural regeneration of stands.

Burning the Forest Floor: — Ground fire is an old practice in decreasing soil acidity and liberating readily available potash and phosphates from organic remains. In the past, forest burning on a large scale has served the purposes of both farming and silviculture; it is still in wide use in northern European countries, as well as on the Atlantic Coastal Plain of America.

Aside from the fire hazard, burning the forest floor is objectionable because it results in a total loss of the most valuable fertilizer ingredient, nitrogen; moreover, the released bases are subject to a rapid leaching in the absence of organic colloids. These ill effects of burning have been emphasized by many writers. In spite of this, the problem of the total influence of the ground fire under different climatic conditions is far from being solved. Several authorities, such as RUBNER (1927) in Germany and HESSELMAN (1928) in Sweden, consider this practice beneficial on strongly podzolized soils with a thick layer of raw humus. The wholly detrimental effect of fire is also denied by many foresters operating on lateritic soils of the United States (HEYWARD and BARNETTE, 1934).

Use of Fertilizers in Forest Stands: — The application of fertilizers in forestry aims to accomplish a dual purpose; first, to maintain an adequate level of fertility in permanently cropped soils of forest nurseries; second, to correct nutrient deficiencies in soils supporting plantations or natural stands. During the past decade, foresters have made remarkable progress in the use of fertilizers in forest nurseries; in this phase of fertilizer practice silviculture has attained as high a level of efficiency as found to-day in agronomy. At the same time, the use of fertilizers outside of nursery beds is still in need of additional research.

According to SCHWAPPACH (1916), general investigations of fertilizer influences on tree growth were initiated by BIERMANN about one hundred years ago. Since that time numerous trials of fertilizer effect upon the growth of plantations were conducted, chiefly in Germany and Austria. A thorough account of achievements in the fertilization of forest stands was given by LEININGEN (1931). In most trials, positive results were obtained with the use of green manure crops, particularly *Lupine* and *Sarothamnus,*

and with the application of organic remains, *i.e.*, humus, forest litter, and slash. Material improvements in the growth of stands due to application of lime or crushed rocks rich in bases have also been observed (SÜCHTING, *1929b;* WIEDEMANN, *1938*; ALBERT, 1938; HILF, 1938). The effect of mineral fertilizers was irregular and often short-lasting. According to some observations, however, application of mineral salts stimulated the recovery of stands injured by drought, insects, or fire; a few papers reported remarkable results achieved with mineral fertilizers on worn-out soils, lacking certain nutrient elements. In many instances mineral fertilizers failed to influence the development of stands, or even depressed tree growth (KODERLE, 1865; RAMM, 1893; GIERSBERG, 1901; VATER, 1911; KUHNERT, 1930).

The effect of fertilizer treatments was more pronounced on soils of a low general fertility, or on soils deficient in some specific nutrients. Soils of adequate water-holding capacity showed more consistent results than coarse and droughty sands. Hardwoods, on the whole, showed greater response than conifers; pioneer species, particularly pines, responded to fertilizer treatments the least (MITCHELL and CHANDLER, 1939; NĚMEC, 1939; WILDE, TRENK, and ALBERT, 1942).

The failure of many fertilizer treatments, as well as the frequently conflicting results of fertilizer trials, may be attributed to a great many causes. Three principal ones deserve to be mentioned: (*a*) Insufficient knowledge of soil chemistry, the action of fertilizers, and nutrient requirements of tree species at the time when most of the trials were initiated; (*b*) Competition of grass and other weed vegetation which often developed vigorously on the fertilized soil and thus deprived the trees of moisture; (*c*) Drought periods which in some cases not only offset the effect of the fertilizer treatment, but even made such treatment harmful; this was especially true when readily soluble mineral fertilizers and peat having high hygroscopicity were applied.

As a rule, the deficiency of nutrients in forest soils is limited to one or two important elements, and only in rare cases is there a need for application of a complete fertilizer. Considerable responsibility is involved in the recommendation of fertilizers for plantations or naturally occurring trees, and such recommendations should not be made without a thorough knowledge of soil conditions, nutrient requirements of species, and the state of available water throughout the growing season.

The fertilizer can be applied either broadcast prior to planting, in planting holes, in borings or slits, as a top dressing, or in solution.

(1) *Broadcast application of fertilizer:* — The area to be fertilized is determined by an approximate survey and is divided into a number of blocks of convenient size for fertilization. In the application of soluble fertilizers, such as muriate of potash, the area is plowed, if necessary, then disked. The desired amount of salt is distributed with a fertilizer spreader or by hand and is worked into the soil by harrowing. In the application of lime or less soluble phosphates, the fertilizer is spread over the soil surface and plowed under to an approximate depth of 6 inches. The soil is then disked, soluble fertilizers are applied, if necessary, and the area is harrowed. The fertilizers should be applied about two weeks ahead of planting.

On sandy soils of exposed areas the plowing and disking may initiate acute wind erosion and, hence, on such areas the use of some other method of fertilizer application may be necessary. Corn may be planted at suitable spacing as an overhead crop to reduce wind erosion on such areas, or strips of rye may be seeded in drills to accom-

plish the same purposes. Only moderate success may be expected with application of readily soluble fertilizers to sandy soils because of the losses through leaching.

(2) *Application of fertilizers in a planting hole:* — A hole, 14 inches deep and 2 feet in diameter, or somewhat larger, is dug. The measured amount of fertilizer is mixed by hand with about three-fourths of the soil from the hole. The soil is somewhat packed, and a wide slit is made with a spade. Into this the roots of the seedlings are lowered, the slit is filled with unfertilized soil which is then firmly packed with the hands and feet. The unfertilized portion of soil should consist predominantly of the humus top soil. This method is limited largely to the application of peat and composts as practiced in road-side, shelterbelt and landscape plantings. An application of mineral salts at the time of planting is inconvenient and requires an extremely careful handling of the entire operation. If carried on by an inexperienced or poorly supervised crew, soluble fertilizers may cause root injury.

(3) *Application of fertilizers as a top dressing:* — Top dressings are usually applied to older trees showing symptoms of nutrient deficiency, or to plantations a few years after the seedlings are set in the field.

The amount of fertilizer *in pounds per acre* needed to re-establish soil fertility is divided by 100. This gives the approximate amount of fertilizer *in grams* to be applied *per each square* foot. The area to be fertilized is determined by the extent of the root systems which ordinarily is indicated by the spread of the crowns. The fertilizing material is measured by means of a calibrated scoop and is applied around the tree excluding a zone in the immediate proximity of the trunk. To prevent the removal of the fertilizer by wind or run-off water, the soil may be worked slightly with a rake or a garden hoe. Readily soluble synthetic fertilizers, such as ammonium sulfate, Ammophos, Nitrophoska, and potassium nitrate, are best adapted to this method of application.

In some instances, good results have been obtained with applications of one- or two-inch top dressings of leaf-mold and other organic remains. However, the top dressings of organic matter absorb a considerable portion of the rainfall which may thus be lost through evaporation. Therefore, a thorough working of organic remains into the soil by spading or raking is very desirable.

Spreading slash is one of the forms of top-dressing fertilization (Ramann, 1890; Möller, 1922; Wiedemann, 1931).

(4) *Application of fertilizers in slits or borings:* — This method is used chiefly in the application of commercial organic fertilizers, less soluble phosphates, and briquette or pellet fertilizers. The slits or borings are made around the base of the tree with an auger, a planting bar, or a spade. A measured amount of fertilizer, or a briquette, is placed in the slit and this is closed with a thrust of the heel. The depth and number of slits vary depending upon the age of the tree and its root extension. Usually, the depth does not exceed 10 inches, and one slit is made for each 10 to 20 square feet of the area. It is important to correlate the distribution of the fertilizer as much as possible with the occurrence of the feeding roots.

The application of composted or other organic fertilizers, compressed into briquettes, appears to be the safest and the most economical method of tree fertilization. However, it is likely to produce results at a somewhat slower rate than the application of fertilizers in solution or as top dressings of soluble salts (Wilde and Wittenkamp, 1942).

(5) *Application of fertilizers in solution:* — Treatments with liquid fertilizers have been recently introduced by landscape architects. Their use is confined to localities where there is a readily available supply of water.

The fertilizer solution is prepared in a barrel or a tank mounted on an automobile chassis. The solution is stirred by hand or by means of installed rotating agitators of a propeller type. The liquid is distributed around the trees using either sprinkling cans or a hose. In some cases, the solution of fertilizer is forced into the soil under pressure through a hose with a sharp-pointed nozzle. In application the nozzle is thrust into the ground and the liquid is allowed to flow for a certain length of time. The same technique is used in treatment of large trees with root growth-promoting substances prior to transplanting. In soils with a high capacity for the fixation of phosphates or exchangeable ions, the forcing of solution into the region of root growth may prove to be advantageous. In many soils, however, the pressure method may

not have appreciable advantages over the ordinary application of fertilizers in solution or as top dressings of readily soluble salts.

Improvement of Soil Fertility by Under-Planting of Soil-Conserving Species: — The aim of this practice is to create an under-story of trees or shrubs which accumulate in their leaves high amounts of bases. The deposition of such litter tends to moderate acidity, increases the content of available nutrients, and subsequently improves the physical properties of soil.

The under-planting or under-seeding of soil improving species is confined primarily to sandy or strongly podzolized soils. Four deciduous species are most commonly used for this purpose: beech, oak, basswood, and hornbeam. Of these only the latter two appear to be entirely satisfactory: beech in some localities contributed to the accumulation of raw humus in stands of pine; oak is too light-demanding a tree to be used under a dense canopy. American maples, notably *A. saccharum* and *A. rubrum,* may play an increasingly important part in silvicultural under-plantings. The results obtained with under-planting black locust are contradictory and the effects of this species are in need of further investigations. In some climatically-restricted areas, European fir was found of considerable value as an under-story in spruce stands.

In spite of considerable improvements that have been sporadically achieved with under-planting, this practice has several limitations: it is costly; the establishment of tolerant and usually exacting species on poor soils encounters difficulties; in regions deficient in moisture the under-story may undesirably increase the competition for available water (Borggreve, 1883). The success of under-planting, therefore, depends on expert judgment and discouraging results are to be expected.

Chapter XIV

SILVICULTURAL CUTTINGS IN RELATION TO SOILS

"Followest not the system as a blind man followeth a wall."

PETER THE GREAT OF RUSSIA

General Principles of Silvicultural Cuttings: — Thinning is a partial cutting of a stand of sapling size or larger, usually conducted as one operation. The chief purpose of thinning is to increase the quality and rate of growth of the stand by eliminating superfluous trees. Selective logging is a partial cutting of mature stands, often conducted over a longer period of time. The main object of selective logging is to obtain natural reproduction of the desirable species (GAYER, 1876; TROUP, 1928; HAWLEY, 1929; BAKER, 1934). In spite of the extensive cut-over areas in this country, the lumberman's ax, if properly used, is just as important a tool of reforestation as the spade or the mattock.

Dead snags, diseased trees, and injured trees, which may serve as breeding centers for parasitic insects or fungi, are removed in all silvicultural cuttings. Furthermore, sprouts, suppressed struggling trees, overdeveloped "wolf" trees, and trees of undesirable species are eliminated insofar as they interfere with the growth of valuable trees. As a rule, cuttings should give enough space for the sound development of each valuable crop tree; yet an adequately dense canopy should be maintained in order to control the growth of grass and sprouts, to preserve soil moisture, and to retard the loss of nutrients. The classification of tree species into "desirable" and "undesirable" is based usually upon their merchantability and has only a relative significance. In numerous cases the commercially inferior species may be of great silvicultural value; they may improve the soil, protect young seedlings from frost and sunburn, control the growth of weeds, reduce the fire hazard, and act as trainers to the crop trees.

In all cuttings, attempts should be made to protect the exposed boundaries of thinned stands by the establishment of shelter belts. For this purpose the boundary of the stand is cleaned of dead material and is carefully thinned so as to give the trees sufficient space to develop a deep crown; the shrubs are left undisturbed, or are cut close to the ground to encourage sprouting. In logging care also must be taken to avoid the formation of frost pockets by cutting passages for air circulation.

Of great importance is the fact that the removal of even a few trees materially affects the conditions of light, temperature, moisture and air movements within the forest stand. Thus, by means of proper cuttings the forester can modify the environment to suit the requirements of different species (MOROZOV, 1912; DENGLER, 1930).

Cuttings exert equally great influence upon the composition of forest soil. From a biological viewpoint, RUBNER (1927) considers clear cutting as a drastic intrusion into the life of the forest; an operation which upsets the

equilibrium of the entire population of forest community, especially that in the stands of tolerant species. With very few exceptions, clear cutting leads to a general deterioration of soil fertility, a fact too well known to American foresters and soil specialists. Table 17 illustrates the state of fertility factors in soils of virgin forest stands and adjacent cut-over areas in northern Wisconsin. Similar observations have been made in a number of European investigations (Burger, 1922; Wittich, 1930). In contrast to clear cutting, carefully conducted selective logging, according to Hausrath (1911), is the form of management in which the soil is not only protected from the extremes of climatic factors, but is benefited by a moderate interruption of a dense forest canopy. Between the two extremes, clear cuttings and conservative selective cuttings, lies the whole scale of transitional forms of forest utilization with correspondingly diversified effects upon soil productivity.

Table 17.—*Analyses of the Surface Soil (7-inch Layer) from Virgin Forest Stands and Adjacent Cut-Over Areas in Northern Wisconsin:*—

Location	Reaction pH	Base Exch. Capacity m.e./100 g.	Total N %	Avail. P_2O_5 Lbs. per acre	Avail. K_2O Lbs. per acre	Repl. Ca m.e./100 g.	Repl. Mg m.e./100 g.
Stand of red pine and white pine, 150-170 years old; Vilas Co.	5.7	6.3	.117	58	160	2.9	.9
Adjacent cut over area	5.9	3.9	.030	23	70	1.8	.4
Stand of hard maple, basswood and associates, 200 years old; Forest Co..........	6.3	14.7	.205	145	270	9.4	2.4
Adjacent cut-over area	5.7	8.9	.064	70	100	3.3	1.8

Intensity of Cuttings:—The spacing of tree trunks after cutting or thinning may vary from 6 to as much as 100 feet, depending upon the age of the stand and other conditions. A proper distance for single trees, however, is determined by the extent of their crowns, and therefore, no regular spacing of trunks can be maintained in silvicultural cuttings. In broad terms, three types of silvicultural cuttings may be recognized with regard to their intensity: *Light cutting,* which preserves an unbroken crown canopy; *moderate cutting,* which slightly breaks the canopy so that each remaining tree has enough space for further development; *heavy cutting,* which leaves the distance between the crowns of remaining trees at least as great as the average crown diameter in the stand.

(1) *Light cutting or thinning* is practiced: (*a*) on sites exposed to strong and dry winds where there is a danger of windfall and loss of soil moisture through evaporation; (*b*) on steep slopes, in order to prevent rapid run-off and erosion; (*c*) on hot and dry exposures, particularly on southern slopes, in order to conserve soil moisture and retard the decomposition of humus.

(2) *Moderate cutting or thinning* is used most commonly. On one hand, this kind of cutting should materially improve the composition of the

stand, eliminate superfluous competing trees, and secure enough light for the crop trees; on the other hand, it should not promote the development of competing vegetation or decrease soil fertility.

(3) *Heavy cutting or thinning* is practiced: (*a*) on cool and moist exposures, particularly on northern slopes, in order to furnish more light for natural reproduction; (*b*) on soils with an abundance of undecomposed organic matter, in order to encourage a more rapid decomposition of raw humus; (*c*) on poorly drained, heavy, or organic soils, when it is necessary to eliminate the inferior or diseased trees.

Cuttings on Different Soils and Sites: — In carrying on selective logging on different sites and with various species, the rate of cutting is subject to numerous modifications governed by local conditions, particularly by the state of reproduction. A few examples drawn from actual conditions will illustrate different procedures employed in silvicultural operations.

Thinnings and Reproduction Cuttings of Pioneer Pines on Sandy Soils: — The stands of jack or Scotch pine are usually thinned at the age of about 20 years. The thinning is carried on with a general tendency to reduce the canopy in the vertical rather than in the horizontal direction. This is done by eliminating largely the codominant and the suppressed trees of the understory, while carefully maintaining the continuity of the canopy formed by the dominant trees. Such treatment of the stand allows more precipitation to reach the ground, but protects the soil from the direct rays of the sun, thereby retarding the decomposition of organic remains. The outlined approach is characteristic of the German School established by Hartig and Cotta (Dengler, 1930).

On sands of the humid podzol region, light-demanding pines reproduce best on southern exposures, where light is abundant. Consequently, regeneration cuttings must proceed in a northerly direction. This method is particularly suitable on sands with a high ground water level. On sands of warmer regions, however, the southern exposures may be too hot and dry even for the drought resistant pines and, hence, the logging must proceed in the opposite direction, *i.e.*, from north to south. The observation of the natural reproduction on different exposures, as it occurs in a given region, will usually indicate the correct direction of cuttings.

Conversion Cuttings of Deciduous Species on Sandy Soils: — The deciduous species occurring on sandy soils include inferior oaks, paper birch and aspen. Because of the low content of moisture and nutrients of sandy soils, none of these species produces a sufficiently high yield and quality of timber to justify thinnings or regeneration cuttings. Consequently, the principal aim of silviculture under these conditions is to convert the deciduous stands into pine forest. This is accomplished by partial cutting and underplanting. On light sandy soil with a deep ground water table competing vegetation is not very vigorous, and the stands may be cut quite heavily, leaving only enough of the best trees to furnish young pines the necessary protection from frost and sunscald. Such intensive cuttings should be adopted only after a thorough examination of soil conditions; the proximity of ground water or a heavier texture of soil may lead to the vigorous growth of competing vegetation which may suppress the underplanted pines.

The improvement of older reproduction of pines mixed with aspen or birch is carried on by cuttings which aim to release the valuable conifers from suppressing deciduous pioneers. These liberation cuts, peculiar to American silviculture, approach in their essentials the French "l'éclaircie par le haut", a thinning that interrupts the canopy of the dominant stand, but maintains an undisturbed under-story for protection of the soil. Theoretically, in a stand thinned by this method, the selected crop trees should have their "crowns in sunlight, stems in shade, and roots in damp ground". The latter condition, however, is not easily attainable in drier regions and on coarse sandy soils (Borggreve, 1883).

Selective Logging of Hardwoods on Mull Loams: — Melanized and slightly leached loam soils with well decomposed organic remains and incorporated humus make an ideal seed bed, and natural reproduction on such soils is easily obtainable. However, a heavy cutting on these soils may lead to the invasion of light-demanding weeds and sprouts which suppress the seed reproduction. Also, a heavy cutting may unnecessarily hasten the decomposition of litter and cause a loss of nutrients, especially nitrogen. For these reasons, hardwood stands on mull loams are logged gradually and very conservatively, following the principles introduced by HEYER (1854). The entire operation consists of four successive cuts and may extend over a period of 20 to 40 years. The control of the composition of the future stand is achieved partly by the elimination of the inferior old trees, and partly by not releasing the reproduction of undesirable species.

The geological origin of soil and its content of nutrients often play a decisive role in determining the ultimate composition of the stand. For instance, in oak-beech-maple stands on fertile trap rock soils of Central Europe, oak grows more rapidly than beech and maple which remain as a suppressed under-story. Therefore, a special effort is made in cuttings to protect beech and maple, if it is desirable to maintain a mixture of all three species. On the other hand, in cutting stands of the same composition on soils derived from calcareous shales, it is necessary to retard the reproduction of beech as much as possible, for it may suppress the other species, particularly oak.

Regeneration Cuttings of Spruce and Hemlock on Podzol Loams: — A thick layer of matted raw humus as a rule retards the reproduction of even the saprophytic conifers. In order to promote the activity of soil organisms and decomposition of organic remains, the amount of light and heat should be increased by a rather heavy cutting. In planning such cuttings, however, a great deal of skill and caution is required. Spruce and hemlock reproduction is liable to suffer injury from frost and sunscald if suddenly exposed. In addition, these species develop extremely shallow root systems on podzol soils and are subject to windfall. For these reasons a heavy selective cutting over a large area is dangerous, and instead the group selection method, or one of its modifications, is usually employed (GAYER, 1876). In this method, the old trees are removed in small patches where some reproduction is already present. The trees are felled in a fan-like formation away from the reproduction. Dragging these trees during removal tends to break up the raw humus layer and encourage additional natural reproduction. In five or more years the cutting area is enlarged by a second concentric cut, or a cut extended in a direction which offers the best protection to natural reproduction. Similar cuts are made at intervals of several years, depending upon the condition of young growth, until the forest in the entire block is regenerated.

Improvement Cuttings and Selective Logging of Mixed Stands on Gley Loams: — Improvement and reproduction cuttings of hardwood-coniferous stands on heavy soils with a high ground water level present one of the most difficult silvicultural problems. As a rule, such soils support a high percentage of inferior deciduous species or trees infected with heart rot. Thus, the condition of the stand usually calls for a heavy cutting; such may also appear justifiable in view of the slow decomposition of organic remains. On the other hand, heavy cutting on wet sites may promote a vigorous growth of hardwood sprouts. Also, a heavy logging may raise the water level and increase the soil moisture to an undesirable extent. This may be partly due to the larger amount of precipitation reaching the ground and partly to the decreased evaporating capacity of the forest stand. As a result, heavy cuttings may encourage the invasion of mosses, particularly *Sphagnum*, and may lead to the development of a swampy condition (MOROZOV, 1930). The more moist and cool the climate, the greater is the danger of such a conversion, and hence gley podzolic soils deserve especially careful handling. Observations of the vegetation and ground water level on cut-over lands and on patches where windfall has occurred serve as an invaluable guide to the establishment of a proper rate of cutting.

Shelter-Wood Strip Cuttings of Spruce and Fir: — This method was originated in Bavaria by WAGNER (1907; 1915), and may not be applicable in other regions. Nevertheless, it represents an example of silvicultural cuttings taking into account a great number of environmental factors, namely, wind, rainfall, frost, snow, dew and

exposure to the sun. In Bavarian forests, the northwestern exposure is most favorable for securing the natural reproduction of spruce and fir. The chief advantages of this exposure are: complete protection from mid-day sun; free admission of the frequent, light western rains, which benefit shallow rooted spruce and fir; formation of dew; protection from the dry eastern winds; the accumulation of snow, which retards early spring growth of seedlings, reduces deer damage and increases moisture in the spring. The northern exposure is slightly less favorable than the northwestern exposure, while the northeastern aspect follows next in order of desirability. The western exposure is favorable in some instances but receives the full afternoon sun. The eastern and southern exposures are decidedly unfavorable.

The regeneration cuts are made in the form of narrow strips laid out with nearly mathematical exactness and extending in an east-west or other predetermined direction. The first felling is made during a good seed year as a clear cut strip, 10 to 20 feet wide, along the north side of the timber block. At the same time a regeneration cut, about 50 feet in width, is made to the south of this strip. This cut removes about one-third of the canopy, and allows the penetration of light and heat, encouraging the growth of reproduction. A release cut is made after reproduction is established. The intensity of the second cut depends upon the species being regenerated and the condition of advance reproduction. The final cut removes all the remaining trees, and is

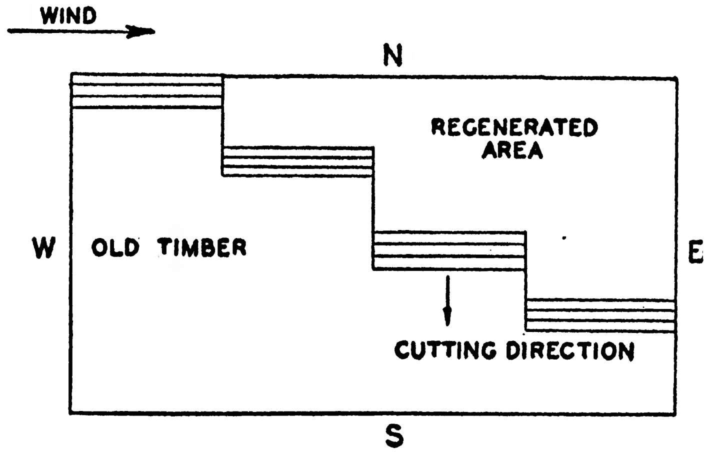


FIGURE 33. — Shelter-wood strip cuttings in steps from north to south. (*After* WAGNER).

made when the young growth no longer needs protection. The cutting proceeds progressively on a number of individual strips until the forest in the entire area is regenerated.

The strip fellings commonly proceed from northwest to southeast. On sites where strong western winds prevail the cuttings are made from north to south. In hilly country the direction of cutting is altered somewhat according to the influence of desiccating sun and wind. At the higher elevations and in northern latitudes, protection from sun may be harmful due to excessive dampness and a rank weed growth. Under such conditions, best results may be obtained by cutting from south to north. The side protection of natural reproduction is obtained by the arrangement of cutting in a step-like fashion. (Figure 33).

WAGNER's system with various modifications may be successfully applied to other tree species.

Wedge Cuttings of Conifers in Mountain Regions: — In mountains or in hilly country, highly satisfactory results have been obtained by EBERHARD's (1922) system, originated in the Württemberg Black Forest. In this method, the logging begins on the side of the block away from prevailing winds. The initial cuts are made at suitable

distances and time intervals in the form of narrow wedges. The logs are dragged toward the base of the slope where a road is constructed for their removal. The regeneration of the stand is achieved by progressive shelterwood strip cuts. The initial cuts begin in the center of the strip and extend outwards on both sides (Figure 34).

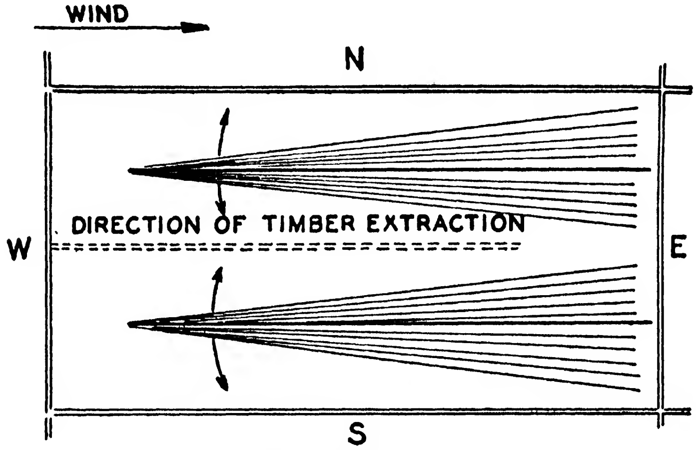


FIGURE 34. — Wedge Cuttings. (*After* EBERHARD).

The principal aims of the system are: to minimize the danger of windfall, to obtain a long regeneration front, and to protect reproduction from damage in log skidding as well as from the adverse influences of the environment. On dry locations the position of wedges should be chosen so as to minimize the exposure of reproduction to direct sunlight.

In carrying out the reproduction cutting, frequent light thinnings are made to encourage the regeneration of tolerant species. The regeneration of the stand may be encouraged by increasing the intensity of thinnings and by reworking the raw humus layer. Old trees are removed as soon as regeneration is established. On sites where downward drainage of air occurs, the point of the wedge must be opened out, making a clear lane from top to bottom through which descending winds may pass.

The few above outlined examples are but a small fraction of all the possibilities which may be encountered in silvicultural cuttings on different soils and sites. In fact, the multitude of conditions resulting from the combination of different tree species with soil, ground water, exposure and slope, make it utterly impossible to prescribe cuttings in terms of standard formulas. Silvicultural cuttings are truly an art, but an art based on science. With few exceptions, the cutting of each individual stand presents a problem of its own, the solution of which depends greatly upon the "savoir faire" of the forester. These are the reasons why the marking of trees for cutting in all well managed forests of Europe is traditionally done by one of the most experienced foresters, often even by the "Herr Forstmeister" himself.

Chapter XV

PRODUCTIVITY OF FOREST SOIL AND FOREST MANAGEMENT

A knowledge of the productivity of forest soil is essential in the solution of several problems in forest management: construction of yield tables; determination of annual cut; calculation of expected financial return on an investment in reforestation or drainage; evaluation of forest land for purchase, exchange or taxation; appraisal of damages to land productivity.

Preparation of Yield Tables: — Yield tables give the volume of the timber per acre in cubic or board feet at various ages, usually at ten year intervals. As a rule, they include information on total number of trees, total basal area, average diameter, and average height of the stand. These data are indispensable in efficient forest management.

Since soils vary in fertility, they produce different yields of timber at any given age. The productive capacity of the land is referred to as "site quality". As there is a fairly close correlation between the height growth of a stand and total production of timber, sites are usually classified on the basis of the average height of the dominant trees at a certain age, such as 50 or 100 years. Thus, a stand of white pine of a high productivity, characterized by an average height of 70 feet at 50 years, is referred to as a stand of site index 70. The approximate yields of a normally stocked stand of this site would range from 3,000 cubic feet at 30 years to 14,000 cubic feet at 100 years.

It has been a common practice in the past to determine the yields on the most and the least productive sites by actual measurement of timber. The yields thus determined were related to age and expressed as curves. The yields of timber for intermediate sites were arrived at by drawing additional curves, equally spaced between those for maximum and minimum productivity. As recent investigations have shown, however, the actual production of timber on different soils does not correspond to these artificial sites established by interpolation. Consequently, the general tendency of modern practice is to measure the growth of a representative stand on land types characterized by definite altitude, topography, soil profile, ground water level (Figure 35), or characteristic ground cover vegetation (Figure 36).

In the construction of yield tables a sufficient number of sample plats is selected to obtain statistically significant data for different sites and age groups. The size of the individual plats varies from ⅛ to 1 acre. On each plat the diameters of all trees are measured with a caliper or diameter tape, heights of trees are determined in sufficient number with a hypsometer to construct the heighht-diameter curve, and age is determined by boring several trees or making stump counts. This information is usually supplemented by a number of complete stem analyses. The data obtained are treated statistically and average values are established. The site quality index and corresponding yields for each soil type for ten year intervals are then presented in the form of tables or diagrams.

With the aid of yield tables, the volumes of growing stands are arrived at by determining the age of the stand and average height of the dominant trees on representative sample plats. The site index of the stand is found by referring to the site index graph (Figure 37), and the yields for this site index are interpolated from the yield table.

Since the volumes of timber shown by yield tables correspond to fully stocked stands, the volume of under-stocked stands is computed by multiplying the normal volume by a reduction factor. The reduction factor is obtained either by ocular estimate, or by measurement of the basal area of the stand. The measurements are usually confined to selected sample plats.

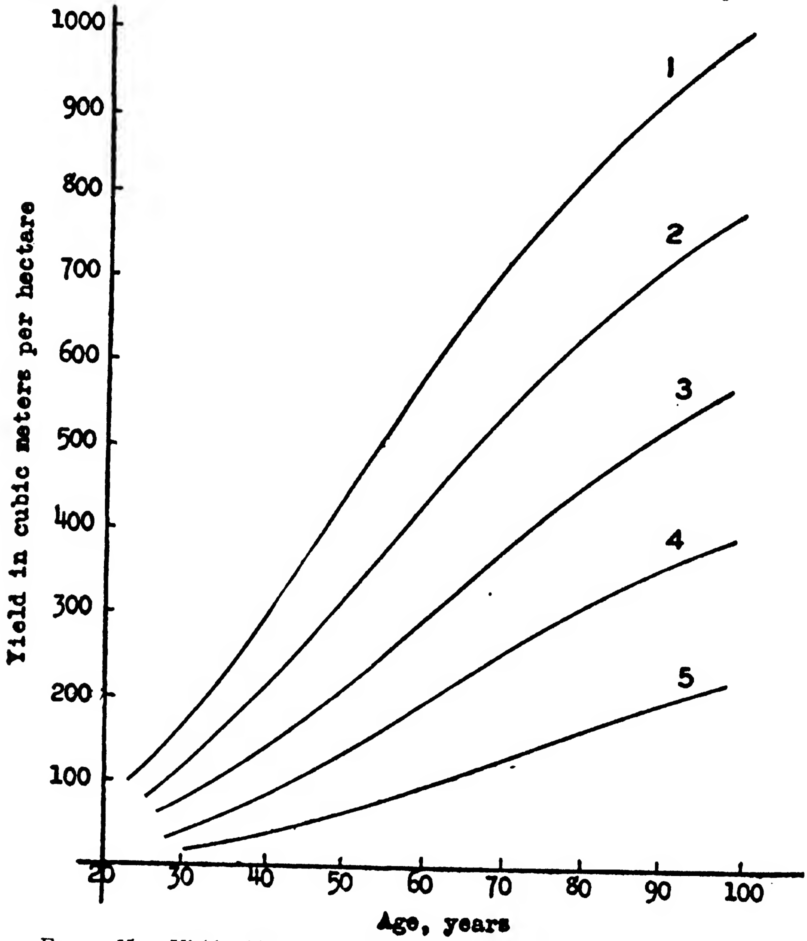


FIGURE 35. — Yield table for Norway spruce of mountain regions by A. v. GUTTENBERG.

Site 1 — "Excellent": Deep humus loams on calcareous substrata in protected localities and at altitudes less than 1,000 meters above sea level. Site 2 — "Good": Fairly moist sandy loams underlain by sedimentary rocks or schists at elevations less than 1,200 m. Site 3 — "Fair": Shallow sandy loams on schists and shallow humus soils on limestone, at elevations from 1,000 to 1,400 m.; deep moist soils of higher elevations. Site 4 — "Poor": Shallow stony soils or wet soils underlain by schists; shallow dry dolomitic soils of southern exposures at elevations from 1,400 to 1,600 m.; better soils of the higher altitudes. Site 5 — "Very poor": Exposed areas of high altitudes, chiefly from 1,600 to 1,800 m.

In case circumstances do not permit the determination of age and height in the field, the site quality may be approximately established on the basis of soil examination or identification of the ground cover association. The direct examination of soil is the only method of establishing the site quality of cut-over lands (WILDE, 1928).

In numerous instances, it is possible to utilize available yield tables after testing their applicability by mensuration studies of sample plats on well defined types of soil. In case the volumes of timber on different soil types do not correspond closely with those given in the available yield tables, it is necessary to make suitable interpolation on the basis of stem analyses.

It is relatively easy to construct yield tables for even-aged pure stands, particularly those of coniferous species, but several complications are involved in dealing with uneven aged and mixed stands. Consequently, the prediction of yields for these stands are subject to considerable error. The technique of yield table construction is described in detail in specific mensuration literature (Bruce and Schumacher, 1935; Matthews, 1935).

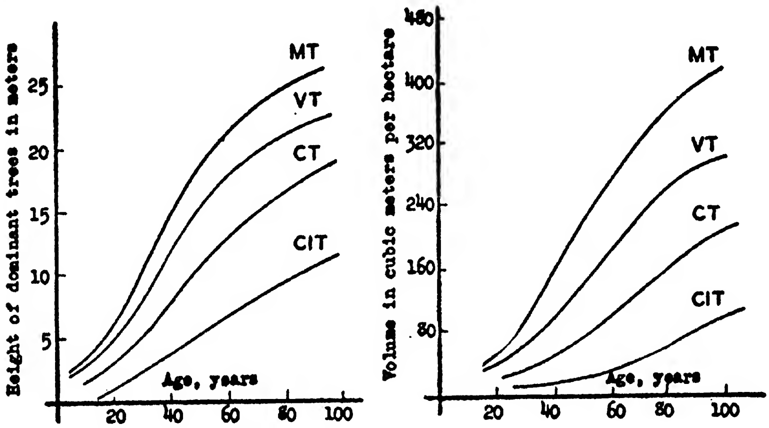


Figure 36. — Yield table for Scotch pine on different floristic sites of Finland: CIT—*Cladonia* type; CT—*Calluna* type; VT—*Vaccinium* type; MT—*Myrtillus* type. (*Adopted from* Y. Ilvessallo, 1927).

Determination of Annual Cut: — The determination of the annual cut under sustained yield management requires a knowledge of the actual volume of timber, as well as the "normal" volume and annual increment of the fully stocked forest tract. If the management unit includes extensive areas of cut-over land to be reforested and areas supporting young growth, the expected normal volume and increment of the management unit must be calculated on the basis of site quality as inferred from the soil survey and the local yield tables. After the actual growing stock is determined by mensuration studies and the normal volume as well as normal increment calculated, the rate of annual cut is established on the basis of regulation formulas, as illustrated below:

$$AC = \frac{NI}{NV} \cdot AV$$

where AC — actual annual cut, NI — normal annual increment of the entire management unit, NV — normal volume of timber, AV — actual volume of timber.

Example: — A forest tract of 10,000 acres supports a total volume of 120,000 thousands of board feet (M.b.f.); the normal volume and normal increment for the same tract are 200,000 and 5,000 M.b.f., respectively. The annual cut would be:

$$AC = \frac{5{,}000}{200{,}000} \times 120{,}000 = 3{,}000 \text{ M.b.f.}$$

Calculation of Expected Financial Return on Reforestation Investment: — Before planting an area to a certain tree species, it is advisable to ascertain the expenses involved, the potential yields at various ages, and the expected return on the investment. The expenses include value of land (L), cost of planting (C), and carrying charges (e) including

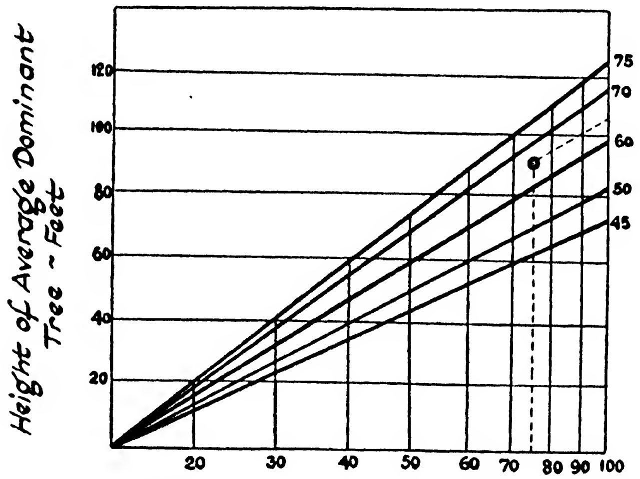


FIGURE 37. — Site index graph for the second growth white pine, Wisconsin. If the height of an average dominant tree is 90 feet at the age of 75 years, the site index of the stand will be 65. (*Adopted from* S. R. GEVORKIANTZ and R. ZON, 1930).

cost of protection, silvicultural care, and taxes. The total cost including compound interest on the capital invested at an accepted rate (p) up to the age when the plantation becomes merchantable (n) is then compared with the stumpage value of the plantation (V) as inferred from yield tables and estimated marked prices according to the following formula:

$$V = L(1.op^n - 1) + C \cdot 1.op^n + \frac{e(1.op^n - 1)}{0.op}$$

Example: —The value of land is \$2.00, cost of planting \$10.00, carrying charges 25c per acre, rate of interest 4 per cent, and the rotation period 40 years. The cost of production or minimum stumpage cost at the end of the rotation will be:

$$V = \$2.00(1.04^{40} - 1) + \$10.00 \cdot 1.04^{40} + \frac{\$.25(1.04^{40} - 1)}{0.04} \text{ or}$$

$$\$7.60 + \$48.00 + \$23.50 \text{ or approximately } \$80.00$$

In case the soil in question is a well drained morainic loam, the expected yield of Norway spruce according to yield tables will be about 40 cords per acre. Conse-

quently the minimum stumpage cost of a cord will be $80.00 ÷ 40 or $2.00 which figure is low enough to promise a reasonable profit. If, however, the soil is outwash sandy loam producing at 40 years only 16 cords per acre, the minimum stumpage value of a cord would be 80 ÷ 16 or $5.00, which figure indicates a possibility of losing money on the investment. Consequently, planting of pine instead of spruce may be more profitable on such a soil (WILSON, 1930).

It must be borne in mind that calculations on the basis of present cost of wood and present value of money are only approximate. Even during a 40 year rotation period the stumpage value of the wood may be greatly modified by changes in the technique of wood utilization, transportation facilities and conditions of the domestic and international wood market.

The Evaluation of Land: — A detailed soil survey is a necessary pre-requisite to land appraisal. The survey should take into consideration all of the factors important in forest production, such as topography, morphology of the soil profile, ground water level, content of humus, soil reaction, and content of nutrients. Particular attention should be given to tracts depleted by fire, cultivation, or grazing (AALTONEN, 1937; SÜCHTING, 1939).

After the survey is completed, a study of current land prices is made. The land of a certain soil type, most advantageously located with respect to transportation facilities and markets, is considered to have the maximum value for this particular soil type. The price of land of a similar soil type located less favorably is computed by means of fractional coefficients, decreasing in proportion to the distance from market and passability of roads. The establishment of reducing coefficients requires a great deal of general experience in the evaluation of land, as well as a knowledge of local conditions.

In some instances, the relative value of forest land (L) is estimated by the capitalization of a permanent periodic income represented by net profit from the sale of timber crops (Y) as follows:

$$L = \frac{Y}{1.op^n - 1}$$

where p is rate of interest and n age of stand.

Example: The value of standing timber at 40 years is $80.00 per acre and total expenses for the period at compound interest are $60.00. Hence, the net income is $20.00 per acre and the value of the land with interest at 4% is

$$L = \frac{\$20.00}{1.04^{40} - 1} = \$5.20 \text{ per acre}$$

If the area to be appraised is cut-over land, the expected yield of timber is determined by consulting yield tables for the species best suited to the soil. The value of land (L) is then estimated by subtracting the cost of planting (C) and raising (e) timber, from the expected total income (V) at the age of maximum merchantability, as follows:

$$L = \frac{V}{1.op^n - 1} - \frac{C.1.op^n}{1.op^n - 1} - \frac{e}{0.op.}$$

Example: — The yield of loblolly pine at the age of 60 years is 25 M.b.f. per A., the stumpage price \$8.00 per M., cost of planting \$5.00 and annual expenses 20c per acre with accepted interest rate of 4 per cent. The value of land is as follows:

$$L = \frac{\$200}{1.04^{60} - 1} - \frac{\$5.00 : 1.04^{60}}{1.04^{60} - 1} - \frac{\$.20}{0.04} \text{ or approximately \$10.00 per acre}$$

The calculations outlined give some idea of land value from a forestry point of view. The figures obtained in this way may serve as a theoretical basis for the evaluation of land in acquisition, exchange, or taxation (WILDE, 1929*c*). However, the actual value of land may be strongly influenced by a number of factors other than soil productivity or the profit expected from the stumpage value. Among these factors the following are of prime importance: danger of fire and extent of fire protection measures, danger of injury by climatic factors and attacks by insects and fungi, stability of wood-using industries, possibilities of future market developments, and the individual interest of the purchaser.

Appraisal of Damage to the Productivity of Forest Land: — Forest soils as well as forest stands may be damaged by a number of destructive agents, such as forest fire, damming of streams, drainage, disposal of waste products, toxic industrial fumes, and grazing. Where it can be shown that a certain person or a corporation is responsible for the alteration of conditions, the owner of the damaged forest tract is entitled to a fair remuneration.

The appraisal of damage to the growing stock is made according to established principles of forest finance. The remuneration for the destruction of a mature stand amounts to the stumpage value of the destroyed timber. In the case of non-merchantable reproduction or plantations the allowable damages consist of the cost of planting or reforestation plus the compound interest on this investment computed from the time of initiation of the stand to the time of destruction.

In order to establish a basis for the evaluation of damages to the productivity of the soil, which will hold in a court of law, the claims should be supported by soil analyses and competent profile descriptions of both damaged and normal soils. The damage must also be substantiated by evidence based on mensuration studies from adjacent localities or on data from authoritative literature. If yield tables are available, they may be used as an index of the decrease in production due to soil deterioration.

The extent of the damage is usually established empirically on the basis of current prices of the normal and deteriorated soil. Otherwise, the amount of remuneration (D) is calculated as the difference between the discounted stumpage price of the expected yields of timber for the original site (V) and deteriorated site (V_1), *i.e.*,

$$D = \frac{V}{1.0p^{a} - 1} - \frac{V_1}{1.0p^{a} - 1}$$

This calculation assumes that the species present are those most suitable to the soil and are at the age of maximum merchantability. Ordinarily, the

cost of planting and the carrying charges are the same on normal and damaged sites; hence, the two values cancel out.

Example: A well drained mull loam soil supported a white pine stand of site index 70 capable of producing 63,000 b.f. per acre at 70 years. Due to the erection of a dam and subsequent change in ground water level, this soil has deteriorated to a gley loam capable of supporting a white pine stand of site index 60, and a potential production of 52,000 b.f. at the same age. If the local stumpage value is \$7.50 per M.b.f. and accepted interest rate 4%, the damages are as follows:

$$D = \frac{63 \times 7.50}{1.04^{70} - 1} - \frac{52 \times 7.50}{1.04^{70} - 1} = \$32.50 - \$27.00 = \$5.50 \text{ per acre.}$$

If the cost of planting is higher on the damaged site, additional claims may be made.

The question of damages to soil productivity is of particular concern in the case of cut-over lands or young plantations.

Chapter XVI

ESTABLISHMENT OF FOREST NURSERIES AND CONTROL OF NURSERY WATERING

Aims and Scope of Nursery Soils Management: — In the early days of silviculture, planting was accomplished by broadcasting seeds on cut-over areas. However, the seedlings produced in this manner were seldom sufficiently vigorous to withstand frost, drought, sunscald, and the competition of grasses and shrubs. Birds and rodents were also responsible for the failure of many direct seedings. This led to the practice of raising seedlings in forest nurseries, *i.e.*, protected areas with fertile soil and artificial irrigation (Tillotson, 1917; Steven, 1928; Toumey and Korstian, 1931).

The seedlings remain in the nursery for one or more years, during which period they are supposed to attain the necessary vigor to survive under the adverse conditions of the planting site. The characteristics which seedlings acquire in the period of their early development in the nursery often decide the fate of plantations. If the planting stock is grown in an unsuitable environment and is under-developed or over-developed, injured by chemicals, or infested with parasitic organisms, one of two results may be expected: either the seedlings will die immediately after being transplanted, or — what is even more unfortunate — they may struggle along for a number of years and eventually become hosts for fungi or insects. Such struggling plantations present a great danger in artificial reforestation, since they provide the breeding centers from which parasites may invade forest stands throughout the region.

The principal aim of nursery soil management is, therefore, to promote a production of vigorous and disease-free planting stock and thus to reduce to a minimum the failure of plantations or their eventual deterioration. This objective is attained by the following means:

(*a*) Maintenance of adequate moisture and aeration of nursery soil by careful watering, cultivation, and addition of organic matter;

(*b*) Maintenance of a proper amount and ratio of available nutrients by the addition of fertilizers and absorbing colloids, by the growing of green manure crops, and by inoculations of the soil with beneficial organisms;

(*c*) Control of soil parasites by application of acidifying agents, fungicides, insecticides, and other suitable measures.

Selection of Forest Nursery Sites: — A management unit in European forests seldom exceeds 10,000 acres. With a common rotation of 80 years, the area to be reforested annually, under management on a sustained yield basis, is, therefore, 125 acres. The planting of this area requires about 250,000 seedlings, *i.e.* planting stock which can be produced annually in a nursery less than one acre in size. This amount of planting stock can be successfully raised in a *temporary* nursery located on a recently cut-over area and maintained as long as the natural soil fertility is not exhausted. The practice of temporary nurseries has many advantages, but it is not applicable at all to a large-scale American reforestation program. The need for hun-

dreds of millions of seedlings calls for the employment of mechanized mass-production methods and equipment, the full utilization of which is possible only in well organized *permanent* nurseries managed by highly trained personnel.

The establishment of a modern permanent nursery requires a considerable investment for grading, fencing, over-head watering system, office building, cold storage house, garages, and other equipment. Therefore a nursery once established cannot be moved to another place without the loss of many thousands of dollars. On the other hand, a poorly selected nursery handicaps reforestation because of the high production cost of seedlings or because of inferior planting stock.

The person who is appointed to select the nursery site should bear in mind that he may be held responsible for the difficulties which may arise in growing stock. For this reason, it is well worthwhile to invite the advice and criticism of experienced nurserymen and specialists in forestry, soils, and plant pathology. A written statement by these specialists is always more valuable than suggestions made by word of mouth. Investigation should embrace the physiographic factors, properties of the soil, biological aspects, and economic conditions of the proposed area. The following discussion covers the more important points to be considered.

(1) *Climatic and topographic factors:* — Localities of extreme temperatures, or those having late spring and early fall frosts should be carefully avoided. If possible, the nursery should be located in the proximity of large lakes or other bodies of water which moderate climatic extremes. The length of the growing season and other climatic conditions of the nursery site should not greatly differ from those of the region to be reforested. An oft expressed recommendation to locate the nursery in the warmest part of the region, particularly at the foot of high mountains, has proven erroneous; in such localities the seedlings of spruce and other microthermic species sprout too early in the spring and are frequently injured by late frosts (MALEIEV, 1933). The area should be protected from wind; otherwise the seedlings may be damaged by blowing sand and by excessive evaporation during snowless fall and winter periods. The action of wind may be reduced to some extent by planting wind-breaks of rapidly growing trees and shrubs, or corn, sunflowers and similar plants. In hilly country, the northern exposure is usually preferable because of reduced danger of early frosts. The relief of the area and arrangement of the protective cover should allow for the drainage of the cool air preventing the development of a "frost pocket". The conditions of climate attain particular importance in mountain regions.

A level area is most desirable in the great majority of cases. On heavy soils, however, a gentle slope may be beneficial because of the better surface drainage. Slopes of a considerable gradient are subject to erosion or "washing off" of seed beds. Seedlings in depressions, even slight ones, suffer from a periodic excess of water and from heaving. Slopes of moderate gradient may be terraced and small rough areas or depressions leveled by grading. However, both terracing and grading are not very desirable because they tend to expose the less fertile subsoil and require considerable additional expense. Care should be taken not to locate the nursery within a zone subject to periodic inundation.

(2) *Soil factors:* — Forested soil or recently cleared soil with preserved forest litter and incorporated humus is much more desirable than similar soil of cultivated, burned-over, or sodded areas. The soil should be at least 4 feet deep and should not exhibit radical differences in the composition of its genetical horizons; soils including impervious inter-layers of shale, "claypan", iron concretions, cemented "ortstein" horizon, calcareous substratum, or greenish mottling of the gley should especially be avoided. The undesirable features of the deeper soil layers will become more pronounced if the surface soil is partly removed in leveling the area. The minimum allowable depth to the ground water table varies between 4 and 5 feet. The dryness

of the surface soil in summer or fall may be grossly misleading as to the position of the ground water and a thorough examination of the soil profile is imperative.

Sandy loams or better sandy soils containing from 15 to 20 per cent of silt and clay particles, are preferable. Lighter soils may be improved by the addition of organic matter or, in some cases, clay. Soils high in colloids are undesirable because of difficulty in cultivation, weeding, control of parasites, and adjustment of reaction. In cold regions heavy soils remain frozen late in the spring, and in lifting the seedlings for planting, the roots may be seriously injured. Also, on heavy soils the seedlings often suffer from heaving or "freezing out". The improvement of heavy soils by the addition of sand or charcoal is seldom practicable. Special attention should be given to the content of gravel and stones embedded in the upper one and one-half foot layer of soil since these skeletal materials will interfere greatly with cultivation and will increase the cost of production.

The optimum reaction for most species is between *p*H 5.0 and 6.0. Soils of a lower *p*H have a low content of available nutrients and may be toxic to seedlings; soils of a higher *p*H encourage the invasion of fungous diseases. Alkaline soils usually present a much more difficult problem than strongly acid soils.

An approximate minimum content of nutrients in the upper soil layer may be indicated as follows: total nitrogen — 0.1 per cent; available phosphorus pentoxide (P_2O_5) — 70 pounds per acre; available potash (K_2O) — 150 pounds per acre; total replaceable bases — 4 milliequivalents per 100 grams, provided the base exchange capacity of soil is lower than 10 m.e. per 100 gms. The content of nutrients can be adjusted without great difficulty by the addition of fertilizers. It is important to ascertain that the soil does not contain soluble salts, carbonates, active aluminum, and similar toxic substances in high concentrations. If the area has been used before as a nursery or for raising truck crops, it is necessary to determine the content of arsenic which might have been introduced for the control of insect parasites.

It is highly desirable that nursery soil have at least 2 per cent of organic matter in the upper 6 inch layer. In most instances, the productivity of a permanent nursery sooner or later will become dependent upon the supply of organic matter which is used for the improvement of the physical condition of soil, as a source of nitrogen, and as a carrier of fertilizers. Therefore, it is essential that some suitable deposits of acid peat are located within a reasonable distance from the nursery.

(3) *Biotic factors:* —The possible occurrence of parasitic fungi and insects should be investigated in the field and by greenhouse tests. The presence of parasites is to be expected in most soils of abandoned fields. It should be made certain that the soil contains mycorrhizal fungi; in doubtful cases this can be verified by greenhouse trials. The biological activity of the soil can usually be improved by the generous application of duff or leaf mold from productive forest stands. Such stands should be located within a reasonable distance from the nursery. If possible, areas supporting persistent weeds should not be chosen.

(4) *Economic factors:* — The nursery should be located as near as possible to the center of the planting region so that the transportation cost is low. There should be sufficient area to produce both seedlings and transplants required for planting, taking into consideration periodic fallowing or the cultivation of green manure crops. The possible expansion of the reforestation program must also be considered and the eventual enlargement of the nursery insured by the purchase of sufficient acreage at the start.

The supply of water for irrigation and for drinking must be carefully examined and subjected to laboratory analysis, the pumphouse should be located, and the length of water pipes and the total expense connected with water supply estimated. Special attention should be given to the condition of the roads in the spring; "mudholes" or "swollen creeks" may cause embarrassing delays in delivering seedlings during the planting season. It is important that power and telephone lines be in proximity to the nursery site. Since the most efficient management of a nursery demands the presence of a nursery superintendent and his assistants almost constantly, conditions should allow for the permanent locating of these officials and their families in the vicinity. Housing, accessibility to a populated center, and distance to a school are of primary importance. The availability of labor and distance to settlement should also be taken into account. Sites accessible to the public are preferable; a well-managed forest nursery may well serve for the education and recreation of the general public.

Preparation of Seed Beds: — If the area selected for a nursery site supports a forest stand, it is necessary to make an exact plan of the location of seed beds, roads and buildings before clearing. This must be done in order to preserve in proper places strips of trees and shrubs which would serve as windbreaks or hedges. After the timber is logged, the slash is either removed and allowed to decay in compost heaps, or it is burned in small piles. The stumps are pulled with a tractor and used for fuel; stump holes are filled with soil. The dry season is best suited for pulling the stumps as the soil is easily separated from the roots. The cleared land is plowed, disked and harrowed, or rototilled, and the seed beds are prepared. The cultivation or rototilling of the soil is particularly urgent on sites infested with white grubs or weeds.

Areas of irregular topography must be graded or terraced using a scraper-tractor unit. In grading, the fertile top-soil is moved to one side, the sterile subsoil is leveled and the topsoil is then distributed uniformly over the surface. A contour map, or series of level traverses are essential for the calculation of the cut and fill and the efficient grading or terracing of any extensive area. The utmost care must be taken to grade to a uniform level or slightly sloping surface. Even slight depressions are likely to accumulate water and cause frost heaving or stagnant growth of stock. In soils with a less pervious substratum, provision should be made for establishing tile drainage.

Artificial Irrigation; Its Advantages and Shortcomings: — Under proper management, artificial watering facilitates the preservation of stock during periods of prolonged drought and makes possible the maintenance of an adequate and uniform content of soil moisture (WILLIAMS, 1917). Indiscriminate use of irrigation, however, may cause serious damage to soil fertility and promote the deterioration of seedlings. Excessive watering creates an anaerobic condition, leaches or renders unavailable plant nutrients, and encourages the development of fungous diseases. Besides these direct detrimental effects, excessive watering may be harmful indirectly by developing succulent seedlings vulnerable to injuries by drought or frost.

Rate of Watering: — Most practical foresters adhere to the philosophy that it is better to lose the weaker specimens in the nursery than to raise the stock on excessive moisture and have subsequent large-scale failures of trees planted in the field. In spite of this, even nurseymen who intend to minimize watering often apply considerably more water than seedlings actually need.

In order to establish a reliable control of watering, it is necessary to record the quantity of water and to relate this quantity to the average monthly rainfall. For this purpose the nursery should be equipped with a number of rain gauges, placed inside and outside of the region of artificial irrigation. In a conservative watering, the amount of water added to the soil each month should not greatly exceed the average monthly rainfall. A survey of this problem showed that, in some nurseries, four to five times as much water as the average precipitation for the same period was added during two dry months. Thus, in some instances, artificial irrigation has in effect translocated the nursery from the prairie-border region of the

central United States to an extremely humid climate as found on the Pacific Coast.

In fine-textured nursery soils, the establishment of a proper rate of watering may be materially facilitated by an analysis of the physical properties of the soil. A knowledge of soil aeration is particularly significant since it is a function of two variable factors, the degree of water saturation and soil porosity. Consequently, soil aeration data have the same general significance for all soil types. As long as watering does not lower the aeration of soil below 20 per cent by volume for any considerable length of time, there is no danger of denitrification and other reduction processes. This means that satisfactory conditions for the growth of trees on soils having a porosity of 50 per cent may be maintained with as much as 30 per cent of water by volume in the soil. On the other hand, with soils having a porosity of 40 per cent, only about 20 per cent by volume of water in the soil is permissible. The aeration of coarse sandy soils practically never drops to an undesirable level.

In dry seasons it is advisable to dig into the soil periodically to a depth of about one foot in order to ascertain either by laboratory methods or ocular estimation the penetration of soil moisture and probability of drought. To aid in the maintenance of a proper water supply, several moisture-recording instruments have been devised (HEATH, 1929; ROGERS, 1933; RICHARDS and GARDNER, 1936; SHAW and BABER, 1939; WALLIHAN, 1939; BOUYOUCOS, 1940; STOECKELER and AAMODT, 1940).

Time and Manner of Watering:— Ordinarily, light frequent sprinkling is not as effective as prolonged application of water at longer intervals. Light sprinklings wet only the upper one or two inches of soil and a large amount of water may be rapidly lost through evaporation from the soil surface. In some cases, however, frequent light watering may be advantageous. Only a limited amount of water may be applied at a time on heavy soils when there is danger of denitrification. A certain amount of care is needed in watering soils of low colloidal content which have been treated with soluble commercial fertilizers, as these may be washed out. A careful periodic examination of the development of root systems and penetration of water on a given soil type is essential to the establishment of a proper rate of watering.

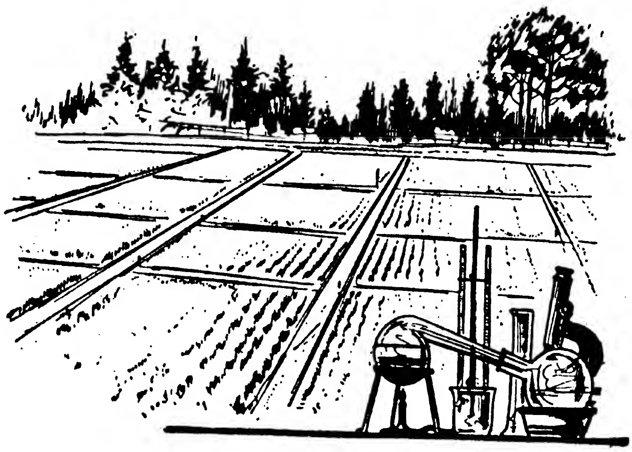
There has been a long, unsettled argument as to the effects of water applied on hot days under direct sunlight. While many nurserymen claim that this practice is harmful to seedlings, some scientists deny the validity of this belief.

Watering on days of scalding temperature decreases the air and soil temperature and often prevents the destruction of stock by heat. At the same time this practice is not economical since rapid evaporation prevents the penetration of water to any great soil depth. The most efficient use of water is obtained when it is applied late in the evening. Such a practice allows the percolation of water to a depth of 8 or 9 inches. Thus, when the temperature becomes high in the middle of the day, the water is protected from evaporation by a soil layer of considerable thickness. The application of water in the early morning, *i.e.*, from 3 to 5 a.m. is almost as efficient as evening watering. As observations showed, in nurseries where

water was applied during the evening and early morning hours, including nurseries without an overhead system, no losses of stock occurred in the extreme drought of 1936 in the Lake States region.

Watering in the daytime is decidedly harmful when the nursery is using hard water because the increased evaporation promotes the formation of a crust of calcium and magnesium carbonates. Although such a crust rarely attains a thickness of more than ⅛ inch, it may cause the deterioration of stock. One-year-old seedlings are particularly susceptible to injury of this kind.

As a protection against frost injury, the operation of the overhead system may become urgent during late spring and early fall nights when the temperature drops suddenly toward the freezing point.



Chapter XVII

USE OF COMMERCIAL FERTILIZERS AND LIME IN FOREST NURSERIES

"I take it upon me to say, that to be a good husbandman, it is necessary to be a good chymist. Chymistry will teach him the best way to prepare nourishment for his respective crops, and, in the most wonderful manner will expose the hidden things of nature to his view."
Dr. A. HUNTER, "Georgical Essays" Ed. 1777

Regardless of the original productivity of the soil selected for a forest nursery, its content of nutrients and organic matter will be depleted in the course of time because of leaching, activity of micro-organisms and nutrition of the seedlings (VONHAUSEN, 1872; SCHROEDER, 1893; VATER, 1905; HELBIG, 1906; WILD, 1910; RETAN, 1914; RUSNOV, 1915; SCHWAPPACH, 1916; HERBERT, 1926; BUCKMAN, 1932; LUNT, 1938). The fertility of soil may be reestablished in a safe and natural manner by the application of litter and duff, or humus from productive forest stands. These materials, however, are seldom available in large quantities and their procurement is costly. In order to bring the nutrient content of a depleted sandy nursery soil to its original state it may be necessary to apply as much as 50 tons of forest duff per acre. Therefore, natural fertilizing materials, as a rule, must be replaced by commercial fertilizers applied broadcast, in the form of compost, or in solution. The following outline contains a description of the more important commercial fertilizers with respect to their suitability to nursery practice (BEAR, 1929; COLLINGS, 1941; LYON and BUCKMAN, 1943).

Organic Nitrogen Fertilizers: — This group of fertilizers includes dried blood, tankage, activated sewage sludge, castor meal, and similar materials containing from 5 to 10 per cent of nitrogen. Although these fertilizers are widely used in nursery practice, none of them is entirely satisfactory. The chief objections are the high price, encouragement of parasitic organisms, and danger of chemical injury of seedlings. The chemical injury occurs under conditions of high temperature which stimulate a rapid release of ammonia.

Mineral Nitrogen Fertilizers: — (1) *Nitrate of Soda* or "Chile saltpeter," $NaNO_3$, occurs as a natural deposit in South America. It is also produced from synthetic nitric acid and sodium carbonate. The refined salt contains about 16 per cent of nitrogen.

Sodium nitrate is soluble in water and readily available to plants. In regions not subject to late frosts, it has special value as an early spring fertilizer since it furnishes the nitrogen to seedlings at a time when the nitrifying organisms are not active. Also, it may be virtually necessary on strongly acid soils, disinfected soils, soils high in raw organic matter, as well as on soils where upland hardwoods or other nitratophilous species are grown.

Continued applications of sodium nitrate may lead to a decrease of soil acidity because of assimilation of the nitrate ion by the plants and accumulation of sodium in the form of the carbonate. This may be schematically represented by the following equations:

$$NaNO_3 + B.x = Na.x + B.NO_3$$

$$2\,Na.x + H_2O + CO_2 \rightarrow 2\,H.x + Na_2CO_3$$

The accumulation of sodium carbonate is detrimental to seedlings of most species, partially because of a decrease of acidity, and partially because of the direct toxicity of the sodium ion. Therefore, the application of sodium nitrate should be limited to cases of urgent necessity. Nitrates should not be applied on seed beds of conifers subject to damping off. Adverse soil conditions resulting from the excessive application of sodium nitrate may be corrected by the application of acid fertilizers, particularly ammonium sulfate.

Because nitrates are easily lost through leaching, they are usually applied in a liquid form for immediate consumption. The common rate of application varies from 100 to 200 pounds per acre at a time. After the application of nitrates, the treated beds should be watered rather conservatively so as to prevent leaching of the fertilizer and to avoid anaerobic conditions which would lead to denitrification.

(2) *Calcium Nitrate* or "Norwegian Saltpeter", $Ca(NO_3)_2$, is produced from lime water and synthetic nitric oxide. This fertilizer contains about 16 per cent of nitrogen and is readily soluble in water. It could be used to advantage on strongly acid nursery soils deficient in calcium. However, it is highly deliquescent and expensive. In other respects it is similar to nitrate of soda.

(3) *Ammonium Sulfate,* $(NH_4)_2SO_4$, is a by-product of coke or coal distillation. It is also manufactured from ammonia, calcium sulfate and carbon dioxide. It contains about 20 per cent of nitrogen. The salt is easily soluble in water and, under favorable conditions, its ammonia is quickly converted into the nitrate form by nitrifying bacteria. This makes the nitrogen in ammonium sulfate available to the plants almost as readily as that in nitrate fertilizers. A great number of the coniferous species appear to have the ability to utilize ammonia nitrogen without its conversion to the nitrate form. Because the ammonia is energetically absorbed by the soil colloids, and used by plants, the sulfate ion accumulates and produces an acid reaction according to the equation:

$$(NH_4)_2SO_4 + 2\,H.x \rightleftarrows 2\,NH_4.x + H_2SO_4$$

In most cases an acid reaction is beneficial to the seedlings, and hence, ammonium sulfate is, in general, a much more desirable commercial nitrogen fertilizer than sodium or calcium nitrate. This is particularly true when coniferous stock is grown. The acidification of a soil through the application of ammonium sulfate serves in a measure to control parasitic organisms. An especially valuable property of ammonium fertilizers is that the ammonium ion enters the soil exchange compound where it may be retained for a long period (Truog, 1938).

Although ammonium sulfate contains more nitrogen per unit than the nitrate fertilizers, it is more slowly available and may be applied at a rate as high as 300 pounds per acre. In some cases it is advantageous to combine sulfate of ammonia with nitrate of soda in a ratio determined by soil conditions and composition of stock. Because ammonia is liberated by alkalies, ammonium sulfate should not be mixed with lime, potassium carbonate, wood ashes, or similar basic materials before application.

(4) *Ammonium Nitrate,* NH_4NO_3, is manufactured synthetically from nitrogen of the air. The pure salt contains 35 per cent of nitrogen of which half is in the form of ammonia and half is in the form of nitrate. This highly concentrated, double salt fertilizer may be of special value in liquid treatment. Recent extensive production of ammonium nitrate for war purposes promises to reduce its cost. Advances have also been made in decreasing the hygroscopicity of ammonium nitrate thus making it one of the most desirable sources of nitrogen for nursery practice. One hundred pounds per acre at a time is a high application of ammonium nitrate.

(5) *Calcium Cyanamid,* $CaCN_2$, is manufactured from calcium carbide through which nitrogen gas is forced at a high temperature. It contains from 20 to 25 per cent of nitrogen, and breaks down in the soil into ammonia and nitrates:

$$CaCN_2 + 3\,H_2O \rightarrow CaCO_3 + 2\,NH_3$$

$$NH_3 + 2\,O_2 \rightarrow HNO_3 + H_2O$$

In the course of these changes some toxic compounds are formed, and the fertilizer cannot be applied shortly before seeding or planting nursery stock. For this reason, calcium cyanamid finds little use in nursery practice.

Phosphate Fertilizers: — (1) *Rock Phosphate,* CaF. 3 $Ca_3(PO_4)_2$, occurs as phosphorite rocks. It contains about 70 per cent of tri-calcium phosphate or about 33 per cent of P_2O_5. This is soluble only in strong mineral acids and is not directly available to the seedlings. In time, however, the water and carbon dioxide of the soil may convert the tri-calcium phosphate into available mono-calcium phosphate:

$$Ca_3(PO_4)_2 + 4\,CO_2 + 4\,H_2O = CaH_4(PO_4)_2 + 2\,Ca(HCO_3)_2$$

This process is slow and rock phosphates are used for the permanent improvement of soils rather than for an immediate supply of available phosphorus. In some cases, rock phosphate may be advantageously added to the compost made of acid peat. Also, the rock phosphate may be used when strongly acid peat is applied in large quantities on nursery soils, as well as when the soil is treated with sulfur. Inoculation of soil with sulfur oxidizing bacteria, or an addition of duff, may speed up considerably the release of available phosphorus. Some rock phosphates are toxic to forest seedlings because of their high content of fluorine.

(2) *Superphosphate,* $CaH_4(PO_4)_2$, is essentially mono-calcium phosphate and is manufactured from rock phosphates treated with sulfuric acid, as follows:

$$Ca_3(PO_4)_2 + 2H_2SO_4 + 4H_2O = CaH_4(PO_4)_2 + 2\,CaSO_4 \cdot 2H_2O$$

Commercial superphosphate contains from 14 to 20 per cent of available phosphoric acid (P_2O_5), partly in the form of mono-calcium and partly in the form of di-calcium phosphate. The 20 per cent superphosphate is the most common phosphate fertilizer in forest nurseries. The rate of application varies from 100 to 500 pounds per acre.

In case the nursery soil is strongly acid and does not contain a sufficient amount of active calcium, the superphosphate may be converted into insoluble ferric phosphate or aluminum phosphate, which is not available to plants (Prianischnikoff, 1923). This process is called "phosphate fixation" and it may be prevented by the addition of lime or wood ashes. On the other hand, in slightly acid or alkaline soils the superphosphate may be converted back to the less available tri-calcium phosphate. This may be counteracted by the addition of ammonium sulfate and other acid-forming materials.

(3) *Double Superphosphate* or "Treble Superphosphate", known also under the trade name "Multiphos", contains from 40 to 50 per cent of available phosphoric acid (P_2O_5). It is prepared by treating phosphate rock with phosphoric acid instead of with sulfuric acid:

$$Ca_3(PO_4)_2 + 4\,H_3PO_4 = 3\,CaH_4(PO_4)_2$$

Double superphosphate is particularly suitable for use on nursery soils well supplied with calcium, and when large quantities of phosphorous are needed. A single application of this fertilizer may be as high as 300 pounds per acre, assuming that the fertilizer is thoroughly worked into the soil.

(4) *Bone Phosphate.* Bones contain about 50 per cent of tri-calcium phosphate, and about 4 per cent of nitrogen. Bone phosphate is a favorite source of phosphorus in greenhouse and commercial nurseries, chiefly because it provides some extra nitrogen and because it produces no toxic effect upon the plants when applied in large quantities. However, it is an expensive fertilizer which cannot compete in forset nursery practice with the other forms of phosphate.

Potash Fertilizers: — (1) *Muriate of Potash,* or *Potassium Chloride,* KCl, is manufactured by purifying natural potash deposits. It contains nearly 50 per cent of potash (K_2O), is soluble in water, and is for the most part readily available to seedlings. In the soil it splits up into potassium and chlorine ions. The former are absorbed by the colloidal fraction of the soil and utilized by the plants, probably in the form of carbonates; the latter form hydrochloric acid:

$$KCl + H.x \rightarrow K.x + HCl$$

$$2\,K.x + H_2CO \rightarrow K_2CO_3 + 2\,H.x$$

The liberated hydrochloric acid is partly employed in converting calcium phosphates into available form, and is partly leached. In large quantities the chlorine ion is toxic to forest seedlings (Němec, 1932), and where large amounts of potash are needed, potassium sulfate should be used instead of muriate of potash. Because potas-

sium salts are easily washed from the soil in the absence of base exchange material, the need for large and repeated applications of potash fertilizer is to be expected on sandy soils poor in clay and organic matter (WILDE and KOPITKE, 1940). The rate of application of muriate of potash varies ordinarily from 100 to 300 pounds per acre at a time. In purchasing potash fertilizers one should be sure that the salt does not contain borax, which is injurious to plants except in minute amounts.

(2) *Sulfate of Potash,* K_2SO_4, is made by treating muriate of potash with sulfuric acid or magnesium sulfate. It contains about 50 per cent of potash (K_2O). It may be used in somewhat larger quantities than muriate of potash without injury to the roots of the seedlings. In other respects it is similar to muriate of potash.

(3) *Crude potash salts.* The crude sources of potash are kainite, sylvinite, and carnallite. These salts contain from 9 to 16 per cent of potassium chloride with some sodium chloride and magnesium sulfate. The chemical composition varies greatly according to the mine. Materials from some deposits may be toxic to seedlings. Total destruction of the nursery stock has been reported due to the application of large amounts of crude potash fertilizers. The toxicity is directly related to the content of chlorides, especially those of sodium.

Recent evidence indicates that finely ground potassium feldspar is available to coniferous seedlings and may be of particular value in treatment of poorly buffered sandy soils (ROSENDAHL, 1943).

Combined Fertilizers: — This group includes largely synthetic products containing two or three essential nutrients. Combined fertilizers find their greatest use in forest nursery practice in liquid treatments. The following outline reviews the properties of the most important salts suitable for use in nurseries.

(1) *Mono-Ammonium Phosphate,* $NH_4H_2PO_4$, is made by treating phosphoric acid with ammonia and evaporating the solution. It contains about 11 per cent of nitrogen and 48 per cent of phosphoric acid. It is sold under the trade name "Ammo-Phos".

(2) *Di-Ammonium Phosphate,* $(NH_4)_2HPO_4$, is essentially a mixture of mono-ammonium phosphate with ammonium sulfate in the proportion of about 800 pounds of crude ammonium phosphate to 1,200 pounds of ammonium sulfate. The commercial product contains about 16 per cent of nitrogen and 20 per cent of phosphoric acid. It is called "Diammono-Phos".

(3) *Nitrophoska* is a trade name for a group of highly concentrated synthetic fertilizers manufactured in Germany. These are made by bringing into contact solutions of diammonium phosphate, ammonium nitrate, and potash salts, and then precipitating out the resulting salt. The four commonly used grades of Nitrophoska are as follows: No. 1. N-15 per cent, P_2O_5 — 30 per cent, K_2O—15 per cent; No. 2. N — 16.5 per cent, P_2O_5 — 16.5 per cent, K_2O — 21.5 per cent; No. 3. N — 15.5 per cent, P_2O_5 — 16.5 per cent, K_2O — 19 per cent; No. 4. N — 15 per cent, P_2O_5 — 11 per cent, K_2O — 26.5 per cent.

(4) *Potassium Nitrate,* KNO_3, occurs in natural deposits and is manufactured from nitrate of soda and muriate of potash. It contains about 13 per cent of nitrogen and 45 per cent of potash. This salt frequently fills exactly the needs of nursery practice.

(5) *Potassium Ammonium-Nitrate* is manufactured in Germany and is known also under the trade name "Kali-Ammon-Salpeter". It contains about 27 per cent of potash and 16 per cent of nitrogen, one-half of which is in the nitrate form and one-half in the form of ammonia. This fertilizer is made with the object of reducing the hygroscopic properties of ammonium nitrate. It is well adapted to use in forest nurseries.

Lime: — Lime encourages the development of damping-off and other root rot diseases. For this reason the use of lime is confined to nurseries raising hardwoods and coniferous nurseries with extremely acid soils (WILDE and KLIMAN, 1931). In any circumstances the application of lime should be carried on in a very conservative manner. In many instances, the deficiency of calcium and magnesium can be more safely corrected by

the use of calcium phosphates, magnesium sulfate, or organic remains high in bases.

The term "lime" is used in general to designate a number of compounds including the oxides, hydroxides, or carbonates of calcium and magnesium, *viz.,* burned lime or quick lime, air slaked lime, water slaked or hydrated lime, waste lime or by-product lime, marl, ground shell lime, and ground limestone. With few exceptions, forest nurseries use no other forms of lime except ground limestone. This is obtained by grinding calcitic or dolomitic rock. It is agreed that 75 per cent or more of the ground material should pass a 100-mesh sieve, and should contain calcium and magnesium carbonate equivalent to not less than 45 per cent of calcium oxide.

The rate of application of ground limestone on forest nursery soils may be as high as 5 tons per acre. Such a high application may be necessary on soils of rather heavy texture and a reaction of about *p*H 4.0. On less acid and lighter soils the amount of lime is decreased proportionately (ODEN, 1927). The general tendency in lime application on nursery soils should be to apply just enough lime to bring the soil reaction to a *p*H of 5.0 when growing conifers and up to a *p*H of 5.5 or 6.0 when growing hardwoods.

It is highly desirable that lime be applied as far ahead of seeding or transplanting as possible. When ground limestone is not available, and burned or slaked lime must be used, the rate of application should be reduced to one-third. Transplanting or seeding immediately after an application of burned or slaked lime is doomed to failure.

Chapter XVIII

USE OF COMPOSTS, LIQUID FERTILIZERS, AND GREEN MANURE CROPS IN FOREST NURSERIES

Composted Fertilizers: — Composts are made of peat, forest litter or duff, commercial mineral fertilizers, soil and other available materials. All of these ingredients are mixed in a pile or special pit, and the organic matter is allowed to partly decompose and absorb the mineral salts during the storage period. By this procedure is obtained a safe and highly nutritive fertilizer which remains effective for a long period. The knowledge of compost preparation is of ancient date and most likely originated in China (KING, 1926). This practice has been in common use in Europe for at least 300 or 400 years. "And do not spread the compost on weeds to make them ranker . . . .", states one of SHAKESPEARE's characters.

For a long time compost was looked upon only as a source of plant nutrients, and with the development of the fertilizer industry the importance of compost temporarily decreased. Within the last two or three decades, however, studies of the biological and base exchange properties of soil have placed an entirely new emphasis upon the importance of composted fertilizers. It became evident that the chief benefit of compost does not lie in the nutrients released from plant remains, but in the inoculating, catalytic, and absorbing effects of the fermented organic matter (JAKUSCHKIN, 1913; BOTTOMLEY, 1914; MANNS and GOHEEN, 1916; HITCHCOCK, 1928; MAKRINOV and STEPANOVA, 1930; MCCOOL, 1932*a;* WILDE and HULL, 1937; RAYNER, 1939; KRUMM, 1941). In recent years the preparation of composted fertilizers from peat, straw, green manure crops, and other materials have received attention from research workers throughout the world (HUTCHINSON and RICHARDS, 1921; PRIANISCHNIKOFF, 1926; LOGVINOVA, 1929; MCCOOL, 1932*b*; EHRENBERG, 1933; MEYER, 1933; STÖCKLI, 1938). The work of HOWARD and WAD (1931) in India led them to conclude that "taking everything into consideration, Indore compost has about three times the value of ordinary manure".

Compost Pits: — Although compost may be stratified in a heap or in any natural depression, it has been found more economical in silvicultural practice to construct a special pit of wood or concrete or a combination of these materials. The simplest form of pit is made by digging a rectangular hole in the ground and reinforcing the sides with planks and poles. More expensive types are constructed with the bottom and framework of concrete. The most permanent pits are built entirely of concrete, except for removable wooden gates.

A variety of structural designs is possible in the construction of permanent compost pits (Fig. 38). In all of the concrete structures it is advisable to make the bottom of the pit somewhat channeled and inclined at about 5° gradient in order to allow for the drainage of percolating water. The water, saturated with fertilizer salts, is drained into a cistern or barrel by means of an iron pipe imbedded in concrete. The liquid thus collected is sprinkled again over the compost. At least one wall of the structure should be removable to facilitate the loading and unloading of compost. This wall is

made of boards keyed into the concrete. If possible, the pit should be cut into a slope of considerable gradient. If so located, gravity will assist in both loading and unloading the pit. When locating a compost pit it is necessary to provide for the extra space which will be needed for the piling of peat and duff, and for the operation of the shredding machine.

The dimensions of a compost pit vary according to the number of acres to be fertilized annually and according to the rate of compost application per acre. At a fairly high rate of application, such as one cubic foot, or approximately one bushel, per 50 square feet, an area of one acre will require 870 cubic feet of compost. In case the area to be fertilized is five acres, the pit should have a volume of about 4,500 cubic feet. Pits made to the dimensions of 100 x 15 x 3 feet, or 55 x 20 x 4 feet, would satisfy this requirement.

Under ordinary conditions it is necessary to retain the compost in the pit for a period of one or two years. For this reason it is convenient to construct a pit with two compartments, so that each year one can be emptied and refilled.

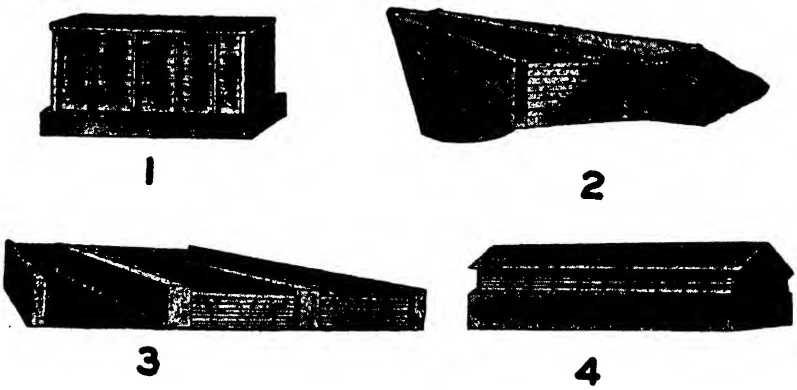


FIGURE 38. — Types of compost pits. 1. Wooden pit with concrete floor, constructed above the ground. 2. Concrete pit with removable end wall, constructed on a side hill. 3. Three compartment pit of concrete framework and removable wooden end walls. 4. Two compartment concrete pit with a roof and removable wooden walls.

Obtaining and Preparing Organic Materials for Composts: — The peat is dug by hand, by means of a dragline, or by steam shovel. If wet, it is left to dry out at the place of excavation, so that a minimum amount of water is transported. The digging of peat, for that reason, should be done in the driest period of the year. The dry peat is transported to the nursery and forced through a shredding machine run by a gasoline motor. The shredding machine is usually attached to the drive shaft or rear wheel of an old automobile.

A thorough examination of the peat, to the depth of possible excavation, is necessary when considering peat for use in forest nurseries (DACHNOWSKI, 1933). Because morphological types of peat show a wide variation in chemical composition, the selection of satisfactory material may be made only with the aid of chemical analysis. Three chemical properties of peat, namely, reaction, total nitrogen content and base exchange capacity are of particular importance in the selection of peat (WILDE and HULL, 1937). The carbon-nitrogen ratio should also be given consideration.

Peat having a reaction of *p*H 5.5 or less was found to be most desirable for forest nurseries, particularly those raising coniferous stock. Peat of a reaction from *p*H 5.5 to 7.0 may be satisfactory for hardwood or transplant nurseries, but is seldom desirable for nurseries raising coniferous seedlings because of the danger of damping-

off and other root diseases. Peat having a reaction higher than *p*H 7.0 is unsatisfactory for the majority of nurseries because of the danger of diseases and toxicity of carbonates. Peat having a total nitrogen content of less than one per cent is considered an unsatisfactory source of nitrogen. Peat having a total nitrogen content of 2%, or higher, is rated a very satisfactory nitrogen-bearing material. A base exchange capacity of peat of 70 m.e. per 100 grams appears to be the minimum allowable, while a capacity of 100 m.e. is quite satisfactory. The use of colloidal or macerated peat in forest nurseries is not advisable since such materials tend to cement the soil particles. Peats with a high C/N ratio are slowly mineralized (JENSEN, 1929), but they may have high exchange capacity and fulfill satisfactorily their function as a sponge absorbing mineral salts.

The duff used for inoculation of compost is raked from the forest floor and packed into burlap sacks. It is transported either in these sacks or piled loosely in a truck which is provided with canvas sidewalls. Since the removal of duff is detrimental to the productivity of the stand, it is not advisable to collect this material from large continuous areas. If possible, the collecting of duff should be confined to ditches, pits, roadside depressions and to other localities where organic remains are accumulated in considerable quantities. In collecting duff as little mineral soil as possible should be taken, since it has a lower value than organic matter. Well-rotted logs and slash debris may also be included as a portion of the duff material.

In the majority of cases it will be found desirable to examine forest duff by laboratory methods, or at least to secure the advice of a person familiar with soil conditions. If this is not possible, a few simple rules will assist in the selection of reliable material: the duff should be secured from a productive upland forest stand, if possible of tolerant species; organic remains developed on soils of calcareous or siliceous origin should be avoided; the duff should be of suitable acid reaction, which may be easily determined by a rapid field test; the duff should have a thickness of at least 1½ inches; duffs from mixed stands, particularly from hardwood-coniferous stands, are usually superior to duffs from pure stands. The higher the proportion of duff or humus, the better the compost is likely to be.

In some instances, the forest debris is replaced by manure. Such substitution is not entirely desirable because manure may encourage the development of parasitic organisms and may infest nursery soil with troublesome weeds. The detrimental effects of manure may to some extent be reduced by prolonged composting (BUCKMAN, 1932; KRUMM, 1941).

Stratification of the Compost: — A 1-inch layer of shredded peat is placed on the bottom of the compost pit. On top of this layer is broadcast a mixture of commercial fertilizers. The fertilizers are covered with about ¼ inch layer of duff, which is followed by a layer of soil, if this is used. The materials are sprinkled with water to make them thoroughly moist. On top of the duff or soil is piled another 1-inch layer of peat, followed by the fertilizers and duff, as previously described. This is repeated until the pit is filled.

The amount of fertilizers to be applied to separate layers of the compost is calculated from the total amount of fertilizers used per acre, and from the amount of compost applied per 100 square feet of seed bed. Suppose that a soil needs 250 pounds of ammonium sulfate, 400 pounds of superphosphate, and 150 pounds of muriate of potash per acre, and that the intention is to apply one cubic foot of compost per 100 square feet of seed bed. Since one acre is about 40,000 square feet, the total amount of compost needed per acre is 400 cubic feet. Consequently, the entire amount of commercial fertilizer needed per acre should be distributed in 400 cubic feet of compost materials. If the compost pit is 48 feet long and 20 feet wide, a one-inch layer will hold 80 cubic feet of compost ($48 \times 20 \times 1/12$). Thus, a five-inch layer of material will be sufficient to fertilize one acre of seed beds. This means that one-fifth of the total acre application of fertilizer must be broadcast over a one-inch layer of organic matter. The application, then, would be 50 pounds of ammonium sulfate, 80 pounds of superphosphate, and 30 pounds of muriate of potash.

For a more exact calculation of the amount of each fertilizer (f) to be broadcast over a one-inch layer of organic material, the following formula may be applied:

$$f = \frac{F \times L \times W}{12 \times 435 \times C}$$

where F is the amount of any one fertilizer to be applied per acre; L is the length of the pit; W is the width of the pit; C is the amount of compost in cubic feet to be applied per 100 square feet of seed bed.

According to this the amount of ammonium sulfate to be applied in the above case would be:

$$F = \frac{250 \times 48 \times 20}{12 \times 435 \times 1} = 46 \text{ pounds}$$

In place of stratification some nursery men feed the shredding machine by means of a conveyer, supplying peat, duff, mineral fertilizers, and soil in desirable proportions. The proper amounts of peat, duff, and commercial fertilizers are applied to the conveyor by means of shovels and scoop cups of known volume. It appears that the materials are mixed in this way more effectively than in stratification. For maximum efficiency the shredding machine should be placed on the very edge or rim of the pit, so that the shredded material is discharged directly into the cavity.

In order to facilitate the incorporation of salts with organic matter, the compost should be kept moist and reworked at least once, but better several times, during the year. This is facilitated by the use of motorized equipment. Prolonged excessive wetness may cause unfavorable biological and chemical changes in the composition of the forest debris.

According to general belief, the compost attains its best quality when it becomes a uniform mass, so that the separate constituents can no longer be recognized. Such decomposition is of rare occurrence in silvicultural practice dealing with acid and resistant types of peat and the degree of compost decomposition plays only a minor part in soils of forest nurseries. It is extremely important, however, that the compost have a sufficient amount of available nitrogen. This must be determined by periodic analyses and the deficiency corrected by the addition of soluble nitrogen fertilizers.

Concentration of Fertilizer Salts in Compost: — In small nurseries, as well as in nurseries with fertile soils, an application of compost may correct both the deficiency of mineral nutrients and of organic matter. In large nurseries with soils low in organic matter, it is more economical to correct the deficiency of organic matter by direct application of peat. This makes it possible to reduce the quantity of peat used in composting to the very minimum amount necessary as a carrier of fertilizers. Such practice leads to the use of highly concentrated composted fertilizers carrying as much as 50 pounds of mineral salts per cubic yard of organic matter.

Although concentrated compost offers a financial saving, it may cause chemical injury to the roots of the seedlings. For this reason, the utmost care should be taken to incorporate the concentrated compost fertilizer into the soil to a minimum depth of seven inches. Before application, concentrated compost may be mixed with raw peat in proportions such as 1 : 1, 1 : 2, or 1 : 3, depending upon the deficiency of soil organic matter. This mixing or "diluting", of compost with peat is usually done by forcing both materials through the shredding machine in the desirable proportion.

Rate of Compost Application: — The minimum convenient application of composted fertilizer is about one bushel per 100 square feet. Under exceptional conditions, however, as little as one-half bushel may be applied per 100 square feet, assuming that the compost is thoroughly mixed with raw organic matter.

Since different seedling species require different amounts of fertilizers, it is necessary to make applications of varying amounts of compost. The standard rate of application is established for the prevailing conditions of the nursery soil and for species of average requirements. For instance, in a nursery raising jack pine, red pine, and white spruce, the average rate of application may be one bushel per 100 square feet. For jack pine it may be necessary to apply only one-half bushel of compost, while for white spruce it may be necessary to apply two bushels. The soil conditions may also essentially modify the standard rate of application, and on poorer blocks of the nursery, even jack pine may require an application of one or two bushels per 100 square feet.

The compost contains nutrients in a fixed ratio which is established to meet the predominant requirements of soil. This ratio, however, may not be entirely satisfactory for sections of the nursery which have an unbalanced ratio of nutrients. Under such conditions it is necessary to approach the desirable ratio by application of compost, and to correct the remaining nutrient discrepancies by the later application of liquid fertilizers. The requirements of different species may also call for additional corrections in the ratio of nutrients provided by compost. In the majority of cases available nitrogen is the factor which needs additional correction.

Distribution of Compost in the Soil: — Poor distribution of composted fertilizer in soil may produce in places injury of the roots. A shallow application of compost, aside from the danger of burning, leads to the production of seedlings with superficial root systems (WAHLENBERG, 1929). Adequate development of root systems is achieved by the distribution of compost to a depth of about 8 inches. This is accomplished by the use of a rototiller or by double plowing and disking (WILDE and WITTENKAMP, 1939).

Use of Liquid Fertilizers in Forest Nurseries: — Ordinarily, fertilizers are applied broadcast prior to seeding or transplanting. These fertilizers should provide enough nutrients for the entire two or three year period of seedling growth. If, for some reason, this has not been done, the treatment of nursery stock with fertilizers in liquid form is likely to become urgent. In some cases, even fertilized soils may develop unexpected deficiencies and require an application of fertilizers in solution during the first or second year following seeding or transplanting. The deficiencies may result from a number of conditions, such as heavy rains, unexpectedly high germination of seed, and losses of nutrients through biologic or chemical fixation.

Choice of Fertilizers for Liquid Treatments: — Because of the high availability as well as toxicity of salts in solution, particular care should be exercised in the selection of fertilizers for use in liquid treatments.

A deficiency of nitrogen may be corrected by the application of 16% nitrate of soda, 20% ammonium sulfate, 35% ammonium nitrate, 26% double ammonium sulfate-nitrate, or combined nitrogen-phosphate and nitrogen-potash fertilizers. The choice of either ammonium or nitrate fertilizer depends upon the reaction and biological activity of the soil, as well as upon the species grown. Under average conditions, it is advisable to supply about one-third of the available nitrogen in the form of nitrates and two-thirds in the form of ammonia. A single application of nitrate of soda and ammonium sulfate in liquid form usually varies from 100 to 250 pounds of salt per acre. Ammonium nitrate is used at the rate of 50 to 150 pounds per acre.

Most of the straight phosphate fertilizers are not readily soluble in water and require prolonged stirring to bring them into solution. However, nursery soils are seldom deficient in phosphorus without being deficient in the other two essential nutrients, and the deficiency of phosphorus is usually corrected by readily soluble combined fertilizers, such as Ammo-phos (11—48—0), or Nitrophoska (15—15—19 or 15—11—26). The application of combined phosphate fertilizers varies greatly, depending upon the concentration of the ingredients, but seldom exceeds 400 pounds of salt per acre.

Potash in liquid form may be supplied either as 50% potassium sulfate or 50% potassium chloride. The former is preferable because of the lesser toxicity of the sulfate ion as compared to the chloride ion. Potassium nitrate or "Potnit" (13—0—44) and potassium-ammonium nitrate (16—0—27) are more expensive but valuable sources of potash on soils deficient in both available potash and nitrogen. Muriate or sulfate of potash are applied at the rate of 100 to 300 pounds per acre at a time. A single application of potassium nitrate may be as heavy as 400 pounds per acre.

In the majority of cases, the fertilizer for liquid treatments is prepared by mixing the individual salts in a proportion to satisfy the requirements of the seedlings on a given soil. The combination of ammonium phosphate, potassium nitrate, and ammonium sulfate gives about the most desirable fertilizer for average nursery soils. The main advantages of this combination are: a slight acidification of soil, high solubility of all ingredients, and an absence of undesirable residues.

Concentration of Fertilizer Solution and Rate of Application: — The amount of total fertilizer salts applied at one time in solution should not exceed 600 pounds per acre, whereas the concentration of applied solution should not exceed 20,000 parts per million, or roughly 8 pounds of total fertilizer salts per 50 gallons of water. The following example illustrates the method of mixing the fertilizers in proper amounts.

Suppose the analysis of a strongly acid soil, growing coniferous seedling, showed a need for about 40 pounds of available nitrogen, to be provided partly as ammonia and partly as nitrates, 50 pounds of phosphoric acid, and 100 pounds of potash per acre. These amounts of nutrients may be had by using 100 pounds of ammonium phosphate (11—48—0) and 200 pounds of potassium nitrate (13—0—44), which combination will give 37 pounds of nitrogen, 48 pounds of phosphoric acid, and 88 pounds of potash per acre, or, roughly, per 40,000 square feet. If the fertilizers are to be dissolved in 48 gallons of water and the rate of application is to be 6 gallons per 100 square feet, the following amounts of each salt should be used in the preparation of solution:

$$\text{Ammonium phosphate: } \frac{100 \times 100 \times 48}{40{,}000 \times 6} \text{ or 2 pounds}$$

$$\text{Potassium nitrate: } \frac{200 \times 100 \times 48}{40{,}000 \times 6} \text{ or 4 pounds}$$

As a general rule, the application of a balanced liquid fertilizer, including all three essential nutrients, gives much better results than the application of single ingredients. In the correction of nitrogen deficiency especially, it is advisable to supplement nitrate or ammonia with some amounts of both phosphate and potash even on soils having a fairly high content of these two nutrients. The complete solutions prevent possible disbalance in nutrition which may result from the higher availability of dissolved salts as compared with nutrients present in the soil in the form of minerals or replaceable ions.

Distribution of Fertilizer Solution: — In the treatment of smaller areas 50 gallon barrels are conveniently used for dissolving the salts. The liquid is distributed with 12 quart cans, one can per 4 by 12 foot bed. The amount of liquid in a 50 gallon barrel will thus suffice for the treatment of 800 square feet. The salts are added to the barrel by using measuring scoops cut from tin cans to the proper size, according to the weights of individual fertilizers used.

Because application by hand is slow and costly, small tanks or barrels mounted on wheels were used in some nurseries. However, this type of equipment fails to maintain a constant concentration of applied solution and does not supply the liquid at a sufficiently uniform rate.

In nurseries of a considerable size, the problem is satisfactorily solved by the use of a special sprayer or tank of 200 to 300 gallon capacity, mounted on a one-and-one-half ton truck and provided with a pressure pump and a rotating agitator (Brener, 1939). The agitator facilitates the dissolving of chemicals and prevents the formation of a precipitate, while the pressure pump assures a uniform discharge of the liquid. The liquid is distributed through two horizontal spraying pipes with 1⁄16 inch nozzles. One of these pipes is mounted in a permanent position and the other on a long swinging rod to make possible the treatment of beds adjacent to an overhead system line.

The sprayer is run in low gear following the paths between seed beds, and the liquid is sprayed over two rows of seed beds. The nozzles are arranged in such a position that the spray is delivered chiefly in between the rows of seedlings, thus minimizing the danger of "burning" the stock by chemicals and decreasing the amount of subsequent watering necessary for washing the chemicals off the leaves. The proper distribution of liquid is achieved by regulation of pressure, speed of the truck and, if necessary, size of nozzles. Ordinarily, the rate of application is fixed to deliver 1 gallon per every 100 square feet traversed. At this rate it is necessary to make 4 trips to apply the required 2 gallons of solution for a 4 by 12 foot standard seed bed. Therefore, the capacity of the tank suffices to treat one hundred standard seed beds or about 5,000 square feet. The relatively slow discharge of the liquid with 1⁄16 inch nozzles is believed to be desirable as the repeated spraying covers the area more completely. According to experience in the Wisconsin state forest nurseries, the efficiency of such a sprayer, considering refilling of the tank, is 400 standard seed beds per hour or about 4 acres per day.

In some instances the solution of fertilizers is forced through the overhead irrigation system. In this method a stock solution is prepared in a large container by dissolving the amount of salts needed for the area to be irrigated. The stock solution is then fed gradually into the system at a sufficiently slow rate to prevent an undesirably high concentration of the

applied solution. The chief objection to this method is the difficulty in obtaining a uniform distribution of liquid over the seed beds. Another disadvantage of this method is that the use of salts may plug or corrode the pipes of the watering system.

Time of Applications of Liquid Fertilizers: — In the spring the fertilizers are most efficient and should be applied as soon as the danger of the last killing frost is over. If necessary, the application of liquid fertilizers may be made in two or even three portions applied at two or three week intervals. The last application should be made at least six or seven weeks before the first killing frost, so as to give the seedlings a chance to harden. The application of liquid fertilizer should be made in the early morning, in the evening, or on a cloudy day. The treated beds should be washed thoroughly with water immediately after treatment.

As a rule, liquid fertilizers are applied to 2-year old stock. Nutrient deficiencies in 1-year beds are often difficult to detect from the appearance of the seedlings and fertilizer application to young stock requires a great deal of caution. Nevertheless, in some instances a light application of liquid fertilizers on 1-0 stock may be more beneficial than heavy applications on 2-0 stock. The seedlings treated during their first year of growth may be allowed considerable time for hardening, whereas the seedlings forced during the second year to meet planting specifications are likely to be succulent and not adapted to adverse field conditions. If under-nourished 2-0 stock is far behind in its development, it is advisable to extend its recovery throughout another growing season, *i.e.,* until the seedlings are 3 years old, or assign such stock to transplant beds. The application of liquid fertilizers to transplants is confined to rare instances.

Timely and appropriate applications of liquid fertilizers must be assured through periodic analyses of soil and careful observations of nursery stock. Frequent analyses are especially urgent in nurseries with poorly buffered sandy soils which are subject to great fluctuations in the level of their fertility.

Liquid Humate Fertilizers: — "Liquid humate" is a term coined recently by nurserymen for a suspension of humus obtained by treating forest litter or duff with a fertilizer solution. Although this term is not strictly scientific, it is expressive and sufficiently accurate to serve the needs of practice.

Liquid humate includes essential nutrients, accessory foods and useful microorganisms. When prepared from suitable types of duff it has a remarkable beneficial effect upon the growth of forest seedlings. Of special practical significance is the reviving effect of liquid humates upon stunted, weakened, chemically burned, and even mechanically injured seedlings. This effect appears to be due to the presence in humates of various growth-promoting substances.

In the preparation of humate for nursery use (Wilde, 1937*a*), enough duff or leaf mold is placed in a barrel or a tank to occupy one-half volume of the container. The required amount of mineral fertilizers is added, and the barrel is filled with water from a hose attached to the water system. While the water is being added, the mixture is stirred constantly and vigorously. After standing for several hours, the mixture is

stirred again to bring fine humus particles into suspension. Then the suspension is siphoned into watering cans and applied to the seed beds in the manner usually followed in applying liquid fertilizers. When fertilizer is applied on a large area, a battery of 12 or more barrels is employed to speed up the treatment. In order to shorten the carrying distance, the barrels are moved, as necessary, from one block of the nursery to another. The organic residue absorbs a considerable amount of fertilizer, and is utilized as an ingredient of compost or for the direct fertilization of seed beds.

Preparation of liquid humates requires readily soluble, high grade synthetic fertilizers, such as ammonium sulphate, ammonium nitrate, potassium nitrate, ammonium phosphate, potassium sulphate, and 15.5 — 16.5 — 19.0 nitrophoska. The concentration of salts should not exceed 25,000 parts per million, which is about 10 pounds of total salts per 50 gallons of water. The amount of each fertilizer to use in the preparation of liquid humate, as well as the rate of application of the suspension, depend upon the content of nutrients present in the soil and nature of nursery stock. A formula suitable to an average sandy soil, raising pine species, may be given as an example: 1½ pounds of 11 — 48 — 0 ammonium phosphate, 3 pounds of 13 — 0 — 44 potassium nitrate, and 2 pounds of 20 per cent ammonium sulfate added to 50 gallons of suspension and applied at a rate of 6 gallons per 100 square feet.

Acid duffs derived from productive mixed hardwood-coniferous stands of tolerant species are most suitable for the preparation of liquid humates. Alkaline duffs and duffs from pioneer stands are the least desirable.

The application of liquid humates is expensive and should be limited primarily to stock seriously upset by malnutrition or injured by chemical, climatic, or biotic agents. Liquid humate is the most efficient means of bringing about stock recovery at present available to the nursery manager.

Use of Green Manure Crops in Forest Nurseries: — The practice of raising transitional crops is used in forest nurseries for a triple purpose: to enrich the soil in organic matter and nutrients by plowing under the succulent tissue of *green manure crops;* to prevent the leaching of soluble salts by incorporating them into the tissues of *catch crops;* to protect exposed soil from erosion and weeds by *cover crops.* Both cover and catch crops are usually used as green manure (Pieters, 1927; Buckman, 1932).

Whenever conditions permit, green-manuring is accomplished with leguminous plants which enrich soil in nitrogen. Various species of lupine, soybeans, and cowpeas are commonly used. Satisfactory results have also been reported with a number of other leguminous crops, particularly vetch, beans, clover, serradella, everlasting pea, and black medic. If high cost of seed or soil acidity do not favor raising legume crops, they may be replaced by less exacting non-legumes. The choice of these latter crops is largely limited to rye, oats, and buckwheat (Süchting, 1928; Toumey and Korstian, 1931; Wiedemann, 1931).

The selection of suitable green manure crops is usually dictated by local conditions, but, in general, preference is given to rapidly-growing species having abundant and succulent tops. In most nursery soils the *p*H value confines the selection of crops to Alsike clover, soybeans, yellow lupine, and non-legumes.

The use of green manures has a strong appeal to a nurseryman. This method of soil fertility maintenance does not involve particular difficulties or danger of burning the stock. However, among the many beneficial effects that have been attributed to green-manuring only a few are undisputable under conditions of nursery soils. Green manuring improves physical properties of the soil, especially its structure and water-holding capacity. It exerts a

conserving influence on the soil nutrients, and, in the case of legume crops, augments the supply of nitrogen (Němec, 1935). The liberation of carbon dioxide and organic acids by decomposing tissues are said to increase the availability of nutrients, such as phosphorus, potassium, and calcium. On the other hand, the gains in organic matter and base exchange capacity due to green-manuring are too small to satisfy the requirements of most nursery soils (Cady, 1938). At best, on sandy soils with artificial irrigation green manure crops may help to maintain the level of these two basic fertility factors. Consequently, the practice of periodic rotations of nursery blocks with green manure as a transitional crop is seldom justified.

The toxicity of green manure crops to forest seedlings, danger of white grub infestation, and encouragement of damping-off disease appear to be greatly exaggerated. In most instances these ill effects are brought about by untimely seeding or plowing under of soiling crops or by too early planting of tree seed. The high carbon-nitrogen ratio of non-legume crops is likely to be the condition responsible for inhibited growth of seedlings under unskilled management (Waksman, 1938).

Catch Crops: — As recent studies have indicated, green manures attain their greatest importance in forest nursery practice by serving as "catch crops" for commercial fertilizers (Brener and Wilde, 1941). A comparison of available nutrients determined by analysis with growth data and the results of plant tissue analyses has shown that a considerable fraction of applied commercial fertilizers is temporarily fixed by green manure crops as difficultly soluble organic compounds. These compounds, however, become gradually available in the course of plant tissue decomposition and benefit the growth of forest seedlings or transplants. From the standpoint of nursery stock production, this conversion of mineral fertilizers into slowly acting and less dangerous organic compounds is just as important as the reduction of fertilizer losses through leaching.

In localities where peat is not available, a catch crop is about the safest and most suitable method of fertilization. Under average conditions, 200 to 300 pounds of 20 per cent superphosphate and 100 to 200 pounds of 50 per cent muriate of potash per acre may be suggested as suitable applications before seeding legume crops. In raising non-legumes, these fertilizers should be supplemented with 100 to 200 pounds per acre of ammonium sulfate. The state of available nutrients in soil, however, may considerably modify the amount of fertilizers required. The most serious objection to the use of catch crops is the loss of one growing season.

Cover Crops: — When conditions require a temporary decrease in the production of nursery stock, the area should be kept under a cover crop or be used as farming land for raising corn, potatoes, or other agricultural products. Such a practice helps to protect the soil from water and wind erosion, excessive oxidation, leaching, and infestation with weeds. The beneficial effect of cover crops is unquestionable.

Seeding and Turning Under Green Manure: — As a general rule, green manure crops are seeded in the spring shortly after the nursery stock is lifted. In the years when a large flight of June beetles is expected, seeding must be delayed until the egg-laying period is over.

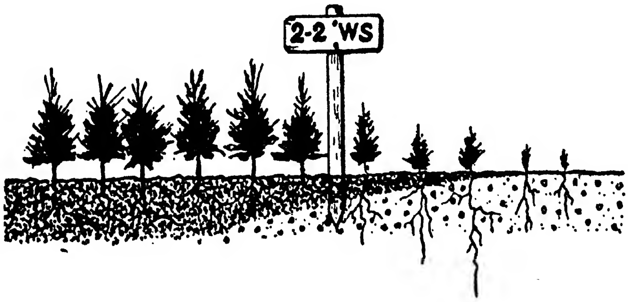
The success of green-manuring with legumes depends upon careful

inoculation of seed with the proper culture of nodule bacteria (Fred, Baldwin, and McCoy, 1932). Some nursery soils have been inoculated by broadcasting surface soil from a field which previously supported a productive stand of legumes. One hundred pounds of soil is sufficient to inoculate one acre of nursery according to Tillotson (1917). This method, however, is costly and not as reliable as seed inoculation.

Plowing under is done before the crop matures or the tops lose their succulence. Allowing green manure to mature may infest nursery beds with an undesirable volunteer crop; this is especially true in raising buckwheat. The decomposition of the hardened tissues, with their high carbon-nitrogen ratio, may bring about a shortage of available nitrogen (Fred, 1916).

In plowing under green-manures, the furrow slice should not be thrown entirely over, but rather against and on the adjacent furrow-slice. In this way the green manure is distributed evenly throughout the whole layer of surface soil. Deep plowing, however, is recommended in nurseries which do not use artificial methods of damping-off control. At the present time, plowing is often replaced by rototilling which incorporates green manure crops very thoroughly with the soil.

The turned under green manure is left to decompose until the plant remains do not interfere with the preparation of seed beds. Forest seed is planted in the fall of the same year or in the following spring. In some instances two crops of green manure are raised during the same growing season, or the green manure crop is followed by a catch crop of non-legumes, usually rye. The second crop is plowed under two or three weeks before the preparation of seed beds. If the cover crop is left over winter, at least two weeks should elapse in the spring between the plowing under of green manure and the planting of forest seeds or seedlings; otherwise germinating seeds and young plants may be injured by the high biological activity and lack of available nitrogen, and may succumb to saprophytic or semi-parasitic fungi.



Chapter XIX

ADJUSTMENT OF NURSERY SOIL FERTILITY

The Problem of Fertility Maintenance in Nursery Soils: — Although the relation of the chemical composition of soil to tree growth was the subject of many investigations in the course of the past hundred years, little reliable information has been obtained (LEININGEN, 1931). In most of the earlier experiments a number of important conditions were overlooked or misinterpreted. The chemical analysis of soils was performed by the use of strong solutions which extracted not only easily soluble or available nutrients, but also difficultly soluble compounds unavailable to plants. No regard was paid to the distribution of nutrients in different soil horizons. The reactions between the nutrient salts, colloids, and other soil constituents were not considered. The studies dealt largely with specific constituents and disregarded the influence of numerous other chemical and biological factors. The production of dry matter alone was studied in fertilizer trials, but the anatomical and physiological development of the seedlings was ignored. Particular attention was given to the encouragement of luxuriant vegetative growth, but not to the development of vigorous seedlings resistant to diseases and unfavorable conditions of environment. In many instances, one-sided fertilization and disruption of nutrient balance led to the deterioration of nursery stock or to the eventual failure of plantations. As a result of this, until recently there has been no agreement among the leaders in silviculture on the problems of nursery soil fertility and the use of fertilizers. Even in Germany, the country with the oldest silvicultural practice, the importance of nursery soil fertilization has been fully recognized only during the past few years. A quotation from DENGLER's (1930) text on silviculture (p. 420) may help to visualize the confusion which existed in German nursery practice: "The earlier, often expressed idea that the planting stock for poorer sites should not be encouraged by fertilization went so far that the commercial nurseries were offering stunted seedlings as being especially well suited for reforestation of the poorer soils."

In a great measure, the opposition to the use of fertilizers in forest nurseries had developed due to a number of misconceptions introduced by the early students of silviculture, especially the theories which discounted the importance of nutrients for the growth of forest plantations and nursery stock. These ideas were based on misinterpreted observations of some mature productive forest stands growing on soils with an apparently low content of nutrients. The trees of such stands, growing widely spaced, are able to utilize nutrients from an enormous volume of soil (DONAHUE, 1937); they store plant food in their leaves, and return it to the soil as leaf litter. In this way, a forest stand with its revolving fertility not only maintains an adequate supply of nutrients, but over a long period may convert barren soil into productive land. Nursery stock, on the other hand, is grown at a great density; its roots seldom penetrate below a 10-inch depth; no crop residues are left in the soil of the nursery because even the root systems are removed. As recent experience has shown, the maintenance of a

satisfactory fertility level in nursery soils often requires applications of fertilizers at much higher rates than is common in farming practice.

Fertility Standards: — Before the technique of soil analysis had been perfected, there was only one way to study the relation of plant growth to the content of soil nutrients, *i.e.*, by greenhouse or sample plat trials. Such methods proved to be of little value in studying the variable and mutually interrelated factors of nursery soil fertility. Moreover, the increase in the size and weight of seedlings, used as a criterion of the fertilizers' influence in empirical trials, is not a measure of the quality of planting stock since its vigor may be lowered by an unsatisfactory root top ratio, succulent tissue, and inferior physiological makeup. For this reason, the entire experimental technique based on MITSCHERLICH's (1909, 1924) concept of "optimum" growth is not applicable to the study of nursery problems. As a rule, stock having the maximum dry weight is too expensive to raise and difficult to plant.

The study of the complex problem of nursery soil fertility would have made slow progress had not HILGARD shown a short cut to its solution. In his text on soils (1906), this scientist warned against "futile attempts to deduce practically useful results from the chemical analysis of *soils long cultivated,* without first studying the less complex phenomena of *virgin soils.*" As the key to the solution of fertility problems HILGARD advocated the investigation of soils under various types of native vegetation which he considered to be the concrete expression of all productivity factors.

Following HILGARD's line of reasoning, several thousand soil-horizon samples were collected under productive stands of representative tree species. These samples were analyzed for pH value, base exchange capacity,

TABLE 18. — *Standards of Nursery Soil Fertility for Several Representative Tree Species:* —

SPECIES	Reaction pH	Base exchange capacity M.E. / 100 g.	Total N per cent	Approximate level of avail. N	Avail. P_2O_5	Avail. K_2O	Repl. Ca	Repl. Mg
				Lbs. per acre			m.e./100 g.	
Jack Pine	5.6	5.0	0.10	20	40	100	2.0	0.5
Red Pine	5.4	8.0	.12	30	50	150	3.0	1.0
*Scotch Pine**	5.4	8.0	.12	30	50	150	3.0	1.0
White Pine	5.4	10.0	.14	35	80	200	5.0	1.5
White Spruce	5.2	15.0	.25	45	100	250	6.0	2.0
*Norway Spruce**	5.2	15.0	.25	45	100	250	6.0	2.0
Yellow Birch	5.3	12.0	.16	35	60	175	5.0	1.5
Hard Maple	5.8	14.0	.20	45	150	275	8.5	2.5
Basswood	5.8	14.0	.20	45	150	275	8.5	2.5
White Ash	6.2	16.0	.22	55	185	300	11.0	3.0

* Standards extended on the basis of practical nursery experience.

total nitrogen, nitrates, ammonia, available phosphorus, available potassium, and replaceable bases. The average fertility of the 8-inch surface layer was arrived at by considering the thickness, volume weight, and chemical composition of the separate soil horizons, *viz.*, litter, duff, layer with incorporated humus, and layer impoverished by leaching. The mean values obtained by statistical treatment of the results of analyses are given in Table 18 (WILDE.

1938; Wilde and Patzer, 1940). These values, representing the average fertility levels of natural seed beds of different species, may well serve as standards in the management of nursery soils. Such fertility levels appear to give the closest approach to the physiological optimum of growth conditions; they provide not only the amount of nutrients, which may be somewhat variable, but the constant ratio of various constituents which is of great importance in the balanced nutrition of seedlings.

While the present list of tree species investigated is far from complete, it may be safely extended to a number of other species either on the basis of practical nursery experience, or on the basis of similarities in natural conditions of growth. Both nursery experience and typological investigations of European students (Morozov, 1930) have indicated that the standards established for red pine and white spruce may be applied to Scotch pine and Norway spruce.

Adjustment of Soil Conditions: —

(1) *Reaction:* — The adjustment of the *p*H value of soil has received considerable attention in both agricultural and phytopathological literature, and only a few specific points need to be emphasized. The acidification of soil may be accomplished by the application of acid organic remains, sulfur, or acid forming fertilizers, such as ammonium sulfate. The need for a decrease of acidity very seldom occurs in nursery practice, being usually limited to blocks with hardwood stock. It may be accomplished by the application of lime, wood ashes, organic remains high in bases, and base forming fertilizers, such as sodium nitrate (Thorne, 1930).

Both decrease and increase in acidity are regulated on the basis of soil analysis and calculation of the amount of material needed, or on the basis of empirical trials.

(2) *Base exchange capacity:* — The correction of the base exchange capacity, as a rule, is achieved through an addition of organic remains, particularly peat. Suppose the exchange capacity of a nursery soil is 7 m.e. per 100 grams, the desired capacity is 10 m.e., and the available peat has a capacity of 120 m.e. per 100 g. Assuming the furrow-slice of soil weighs 2,400,000 pounds, the following amount of peat must be applied to correct the deficiency:

$$\frac{2{,}400{,}000 \times (10-7)}{120}$$

or 60,000 pounds, or 30 tons of dry peat per acre. This corresponds roughly to 120 cubic yards of peat, or 20 large truckloads.

When there is a suitable deposit of clay in the proximity of the nursery, it may be used instead of peat. In case the base exchange capacity of the available clay is 40 m.e. per 100 g., the following amount will be necessary to correct the deficiency of 3 m.e. in 2,400,000 pounds of soil:

$$\frac{2{,}400{,}000 \times 3}{40}$$

i.e., 180,000 pounds or approximately 90 cubic yards.

The chief advantage of using clay instead of peat is that the clay will remain in the soil indefinitely, while peat will decompose in time. However, clays of high exchange capacity and suitable reaction are of rare occurrence.

(3) *Total nitrogen:* — The adjustment of the base exchange capacity by application of organic remains usually brings the content of total nitrogen to a desirable level. If not, the content of total nitrogen is increased by the addition of suitable peat or duff.

Suppose the total nitrogen content of the nursery soil is 0.07 percent and the desired content is 0.12 per cent. The deficiency of 0.05 per cent in 2,400,000 pounds of the surface soil is 2,400,000 × 0.0005 or 1,200 pounds of nitrogen. If the peat to be applied analyzes 2.5 per cent of total nitrogen, the necessary amount of peat is

1,200 × 100 ÷ 2.5 or 48,000 pounds, or about 100 cubic yards per acre.

(4) *Available nitrogen:* — Under favorable conditions, microorganisms provide a sufficient amount of available nitrogen by converting protein compounds into nitrates and ammonia. The usual content of nitrate and ammonia nitrogen together in a nursery soil amounts to about 1 per cent of the total nitrogen, *i.e.*, about 40 pounds per acre, if the nursery soil contains 0.2 per cent of total nitrogen (Russell, 1936). Under such well-balanced conditions there is no need to apply available nitrogen in the form of commercial fertilizers.

In many instances, however, the amount of available nitrogen released by soil organisms may not be sufficient for seedling growth. This may be due to crowded seed beds, presence of raw organic matter high in carbon, or a soil unfavorable for microbiological activity. The latter condition, particularly, may be expected in nursery soils which have been disinfected with toxic substances. In such cases, the content of available nitrogen should be increased by application of ammonia or nitrate fertilizers.

There is at hand no simple procedure for the determination of the exact amount of mineral nitrogen fertilizer to apply, since this depends upon a great variety of factors. Fortunately, deficiency of nitrogen is readily manifested by discoloration of foliage, and consequently, the application of nitrogen fertilizers is usually dictated by the appearance of the stock. A good rule to follow in nitrogen fertilization is to apply too little rather than too much. A deficiency may be corrected by a second application; an excess produces planting stock lacking in vigor.

As analyses of virgin soils and nursery experience have indicated, the state of available nutrients should approach the ratio of 1-2-5 or 1-3-5, if vigorous, well-balanced stock is to be produced. This means that in soil with 100 pounds of available phosphorous pentoxide and 250 pounds of available potash, the maximum single application of nitrogen fertilizer should not exceed 50 pounds of elemental nitrogen, or 250 pounds of 20 per cent ammonium sulfate, or an equivalent amount of any other nitrogen fertilizer. An application higher than 60 pounds of elemental nitrogen would seldom be justified.

(5) *Available phosphorus:* — A deficiency of available phosphorus is corrected by the application of phosphate fertilizers. If a soil analyzes 30 pounds per acre of available phosphorus pentoxide (P_2O_5) and the desired content is 80 pounds, the deficiency of 50 pounds may be supplied by an addition of about 100 pounds of 45 per cent treble superphosphate or 250 pounds of 20 per cent superphosphate.

(6) *Available potash:* — A deficiency of available potash is corrected by a method similar to that for phosphorus. For instance, if the soil content of available potash (K_2O) is 100 pounds and the required amount is 200 pounds per acre, the deficiency of 100 pounds is met by the addition of 200 pounds of 50 per cent muriate of potash or sulfate of potash.

(7) *Replaceable bases:* — Deficiency of calcium and magnesium is seldom experienced in nursery soils. If the content of bases is too low it may be gradually built up by the addition of organic remains high in bases. Organic materials with a high base content are not necessarily alkaline in reaction, and hence not dangerous in nursery use. Also, the application of low-grade phosphate fertilizers and magnesium salts may contribute to the correction of deficiencies.

Ordinarily, soil improvement involves a period of several years, and follows a definitely outlined program. The length of time needed for soil building depends on a number of factors, such as present condition of soil in relation to the desired state, species of trees being grown, and availability of funds. Experience has shown, however, that most soils can be brought into a fully productive state in the course of three 2-year rotations.

In outlining a soil improvement program it is important to keep in mind the relationship that exists between the total soil fertility, the fraction of nutrients in the soil solution, and the content of nutrients actually required by seedlings during their 1- or 2-year period of growth. The amount of nutrients necessary for the actual annual metabolism of forest seedlings con-

stitutes, as a rule, but a small fraction of the total available supply of nutrients present in a productive nursery soil. For example, the amount of calcium annually taken up by the growth of even calciphilous hardwood seedlings is less than 1 milliequivalent per 100 gm., or 400 pounds per acre (STONE, 1940). Nevertheless, a productive hardwood nursery soil must contain at least 5 milliequivalents per 100 mg. of replaceable calcium, or 2,000 pounds per acre. The presence of this high amount is vital because calcium fulfills numerous functions in soil besides that of a plant nutrient; it promotes aggregation, regulates reaction, counteracts the toxicity of other ions, and stimulates the activity of microorganisms.

In nursery soils, exposed to rainfall and artificial irrigation, the nutrients in solution are subject to frequent changes. During a period of abundant rainfall, the readily soluble salts are leached away and the soil is saturated with nearly pure water. After the rains have stopped, additional nutrients are gradually released into the soil solution, by hydrolysis and the activity of microorganisms, from the more soluble minerals, exchange material, and organic compounds, *i.e.*, from the storehouse of the plant nutrients (TRUOG, 1938). The higher the reserve supply of nutrients, the more stable is the level of the readily available fraction, and the greater is the assurance of an uninterrupted and balanced nutrition of seedlings.

In recent years, the science of plant nutrition has been broadened by a number of remarkable achievements: nearly dead plants were revived by colloidal suspensions of certain metals; the growth of roots on twigs of conifers was promoted by the use of hormones; high yields were produced in soil-less cultures; many improvements were obtained through the use of vitamins and rare elements, and inoculations with nitrogen-fixing bacteria, mycorrhizal fungi, and earthworm cultures. Unfortunately, not all of the new developments enjoy as yet a full success under actual nursery conditions. To a great extent this is because the applications of new treatments are not always preceded by a careful adjustment of related soil fertility factors. It is obvious that no vitamins, hormones, or colloids can improve the growth of stock if the soil is deficient in phosphates, potash, or any other nutrient.

Effect of Nursery Soil Fertilization upon Survival and Growth of Seedlings in the Field: — In farming or gardening the results of fertilizer applications are judged on the basis of general development of plants or weight of the crop produced. In nursery practice the success of fertilization is measured by the survival and the rate of growth of seedlings after they are transplanted in the field. The information accumulated during the past decade has shown conclusively that under-developed or "starving" seedlings, grown on nursery soils depleted in nutrients, are not satisfactory planting stock. On the other hand, the vigor of planting stock may be upset by either application of fertilizers in injuriously high concentrations, or by unbalanced treatments which produce physiological and anatomical abnormalities of seedlings (SHIRLEY and MEULI, 1939; CHAPMAN and LIEBIG, 1940). Tables 19 and 20 present some results obtained under field conditions with variously fertilized nursery stock (STOECKELER, 1940; WILDE, WITTENKAMP, STONE, and GALLOWAY, 1940).

TABLE 19. — *Survival and Height Growth of 2-Year-Old Jack Pine Raised on Beds of an Average Fertility and Those Treated with a High Rate Application of Complete Fertilizer. Results Recorded 3 Years After Planting Seedlings in the Field* (After WILDE, WITTENKAMP, STONE and GALLOWAY): —

PLAT	Unfertilized stock		Fertilized stock	
	Survival	Height	Survival	Height
	Per cent	*Inches*	*Per cent*	*Inches*
A	73	24.9	91	37.0
B	83	22.7	87	27.4
C	92	20.9	89	26.6
D	63	25.9	86	25.0
AVERAGE	77.8	23.4	88.3	29.4

Average increase in survival: 88.3 — 77.8 = 10.5 per cent.
Average increase in height growth: 29.4 — 23.4 = 6.0 inches.

TABLE 20. — *Effect of Complete N-P-K Fertilizer and Acid Peat Applied Broadcast upon Survival of 1-0 Jack Pine Seedlings. (Adopted from Technical Notes of the Lake States Forest Experiment Station, No. 162, 1940)*: —

NURSERY TREATMENT PER ACRE	CLASSIFICATION OF NURSERY STOCK*			FIELD SURVIVAL
	PLANTABLE	GOOD	EXCELLENT	
	Pct.	*Pct.*	*Pct.*	*Pct.*
No treatment	60	12	7	69.6
400 lbs. 20% amm. sulfate, 600 lbs. 20% superphosphate, 160 lbs. 50% potash	95	22	12	70.7
Ditto, plus 20 tons of peat (oven-dry basis)	100	67	47	77.0

* In classifying nursery stock, trees 4/64 inch caliper and over are considered plantable; those 5/64 inch and over are good; those 6/64 inch and over are excellent.

Chapter XX

CONTROL OF PARASITIC ORGANISMS IN SOILS OF FOREST NURSERIES

"It is not the pathogenic microbes, but the state of the infested organisms that counts."
CLAUDE BERNARD

Occurrence of Parasitic Organisms in Nursery Soils and Principles of their Control: — Records of over one hundred years of forest nursery practice include but very few cases in which seedlings on recently cleared land were attacked by parasitic organisms. This suggests that in many instances the invasion of the nursery by parasites is a manifestation of exhausted soil fertility, unskilled fertilization, excessive watering, or the building up of large populations of introduced soil organisms. Therefore, skillful management of the nursery soil appears to be the first requirement in protection of nursery stock from diseases.

If preventive measures fail and parasites invade the nursery, all possible efforts should be made to suppress them by suitable disinfection treatments. In carrying out these treatments it should be kept in mind that the welfare of the seedlings is just as important as the destruction of the parasites. Usually, measures of control destroy not only the parasitic organisms but also the useful population of the soil. Very often such measures materially decrease available plant food and leave toxic residues. For these reasons, the re-establishment of the ruined fertility, through application of "antitoxins", fertilizers, and inoculating materials, forms an essential sequel to disinfection treatments.

The phytopathological literature of today includes numerous methods for the control of soil parasites. Unfortunately, in devising various treatments sufficient consideration has not always been given to the effect of disinfectants on the forest seedlings under different soil conditions and in the presence of various fertilizers. As a consequence, the application of such treatments without a thorough examination of soil may either not eliminate the parasites, or may produce a condition fatal to nursery stock. The reaction of soil, content of colloids, organic matter, carbonates, and exchangeable bases, petrographic origin of soil, and composition of soil solution are among the important factors which modify the kind, quantity, and concentration of the chemicals used in the control of parasites.

The most common and most dangerous parasites in nursery soils are the damping-off fungi which cause the destruction of seedlings in their early period of growth. Outstanding among these organisms are species of *Pythium, Rhizoctonia, Fusarium,* and *Phytophthora* (HARTIG, 1894; HARTLEY, 1921; BOYCE, 1938). Some of these fungi, particularly *Rhizoctonia* and *Pythium,* differ considerably in their habits and require a specialized approach to their control (ROTH and RIKER, 1943). The destructive activity of damping-off fungi is sometimes supported by mites (*Arachnida* spp.) which appear to be instrumental in transmission of the infection (HANSSON,

1936). The disease may also be initiated or promoted by nematodes, particularly by species of *Iota* (TOUMEY and KORSTIAN, 1931) and *Rhabditis* (WILDE, 1936), which have been found in the roots of injured seedlings of slash pine and red pine, respectively. Less conspicuous but perhaps not less important than damping-off fungi are their close relatives that cause the root-rot of older seedlings and transplants, *viz.* species of *Fusarium* and *Phytophthora* (RATHBUN, 1922). Among the insect parasites, the white grub, *Phyllophaga,* root weevil, *Brachyrhinus,* and mole crickets, *Gryllidae,* should especially be mentioned (GRAHAM, 1929; METCALF and FLINT, 1939).

The following discussion reviews the methods of parasite control commonly used in forest nurseries. The purpose of this outline is to give a cross-section of various approaches to the problem and hence it includes methods of dubious value in nursery practice.

Surface Firing: — The burning of brush, wood, or straw is the oldest and most primitive method of soil sterilization. Twenty centuries ago VIRGIL in his Georgics said, "Often you will find it well to burn the garnered field and set the flimsy straw a-cockling in the flames. Whether perchance the land in this wise finds some unknown force, or that every fault thereby is purified by fire and all the useless humours purged . . . ."

Until recently, surface firing has been widely used in agricultural and horticultural practice as a means of damping-off control, but has been almost abandoned because of the scarcity of wood. Although in some trials surface firing proved to be satisfactory in forest nurseries, no conclusive results have been reported. Since wood ashes and the decreased acidity following burning may encourage the development of surviving damping-off fungi (ANDERSON, 1930), this method requires a careful investigation of its reliability under local conditions before it is used on a large scale.

Steaming of Seed Beds: — While sterilization by steam may be found practicable under special conditions, there have been but few experiences with this method in forest nursery practice (SCHEFFER, 1930). Sterilization of the soil by steam lowers the fertility, because of the destruction of some useful organisms, breaking down of soil colloids, and excessive accumulation of soluble salts. Quite often in steam treatments some portions of the soil remain unsterilized and the surviving parasites, within a short time after treatment, invade the treated areas with increased intensity.

Use of Fungicides and Insectides: — This is the most common, but not necessarily the best method of parasite control.

(1) *Sulfuric acid:* — A dilute solution of sulfuric acid is about the cheapest and most commonly used means for the control of damping-off disease (SPAULDING, 1908; JOHNSON, 1914). However, this method is primarily adapted to non-calcareous soils of sandy texture. This method is treated here at some length because the problems encountered with it are often representative of those with other chemicals.

The dilute solution is prepared in a barrel or another large non-metal container by the addition of concentrated commercial acid to water with constant stirring. Water must not be poured into the acid as this may cause an explosion and dangerous acid burns. It is well to keep a solution of ordinary baking soda (a tablespoon full per quart) handy to place on skin or clothing that is accidentally wet by acid.

The solution is transferred from the barrel by means of a hose or spigot into watering cans and sprinkled uniformly on top of the seeded nursery beds. As soon as the acid has soaked into the soil, the soil is thoroughly watered and is kept in a fairly moist condition throughout the period of germination and early growth of seedlings. Allowing the soil to dry out may cause injury to the seedlings. The success of disinfection depends upon a correct estimation of the concentration of solution to be applied and the rate of its application (WILDE, 1937*b*).

Treatments with strong solutions in small quantities were based on the assumption that the acid is diluted by water applied later on. However, on soils having even a small amount of base exchange material, most of the H-ions are instantly fixed at

the points of their first contact with the soil; these ions can be released only slowly by hydrolysis and replacement with bases and do not undergo immediate dispersion either horizontally or vertically. Consequently such treatments are likely to result either in incomplete control of parasites or in chemical injury to the seedlings. On the other hand, treatments with weak solutions in larger quantities fails to eliminate the damping-off fungi. Such treatments also lead to saturation of soil to an unnecessarily great depth and subsequent greater deterioration of fertility. Thus, any considerable deviation from the desirable optimum of either concentration or rate of application of solution causes unsatisfactory results, as outlined in the following summary:

(a) *Too strong concentration:* injury of seedlings;
(b) *Too weak concentration:* inadequate control, and reduced fertility;
(c) *Too small volume of solution:* partial control of parasites due to patchy distribution and insufficient penetration of liquids;
(d) *Too large volume of solution:* deterioration of soil fertility to an unnecessarily great depth.

Work in nurseries located on noncalcareous sandy soils showed that the quantity of solution needed to saturate the surface soil layer containing the seed ranges from 6 to 7 gallons per 100 square feet. On soils of sandy loam texture, a somewhat greater amount of solution may be needed.

Observations over a number of years have indicated that 2 per cent by volume is the maximum concentration of sulfuric acid required in the control of damping-off fungi. This concentration is usually not injurious when applied in the fall at the rate of 6 gallons per 100 square feet. In some nurseries the concentration of solution in the fall treatments should be reduced to 1.5 per cent. The use of 2 per cent solution in spring treatments involves danger of chemical injury. A 1.5 to 1.2 per cent solution appears, therefore, to be safer for the treatment of spring sown beds. A further decrease of concentration is not advisable because of the low disinfecting efficiency of weak solutions.

The excess of acid should be removed from treated seed beds by periodic watering so that the reaction of the soil approaches a *p*H of 5.0 at the time of germination. The speed with which the acidity of treated soil decreases depends upon its mineralogical composition and colloidal content. The affinity of some soils for acid is so great that watering will not raise the reaction to a value higher than *p*H 3.0 before the seedlings germinate, and the seedlings may suffer from chemical injury or malnutrition. Other soils have such a small affinity toward acid or such a high neutralizing capacity that watering will nullify the effect of acidification, thus making possible the reinvasion of the surface soil by parasites from the deeper untreated layers. On all such soils the use of sulfuric acid is impractical and some other method of control should be employed.

The fertility of soil decreased by acid treatment should be re-established by liquid fertilizers applied six weeks after germination, or in the spring of the next growing season.

(2) *Nitric acid:* — Nitric acid provides available nitrogen, and has considerably less corrosive effect on soil than sulfuric acid, but is less than half as efficient in killing fungi as the latter. A sufficiently strong concentration for the control of parasites ranges from 3 to 5 per cent. With this concentration the cost is nearly ten times as much as that of sulfuric acid; therefore, nitric acid may be used only on small areas.

(3) *Formaldehyde:* — Formaldehyde treatments are likely to be best adapted for use on soils of heavy texture and soils of neutral or alkaline reaction. The concentration of formaldehyde solution varies from 1:100 to 4:100 of 37 per cent commercial formalin in water. The concentration most commonly used is 2:100.

The solution is applied at the rate of about 6 gallons per 50 square feet at least one week ahead of seeding. Under unfavorable conditions a longer period may be needed for evaporation of the formaldehyde (Young, Davis, and Latham, 1937). It is important that soil disinfected with formaldehyde be disturbed as little as possible at the time of seeding, and especially should not be contaminated by applications of untreated soil as a top dressing.

The greatest drawback in the use of formaldehyde is the difficulty in establishing the proper length of time which must elapse between treatment and seeding. Too short a period results in chemical injury to germinating seedlings, whereas too long a period

may decrease the effectiveness of formaldehyde and may result in more severe damping-off than on untreated areas.

The use of paraformaldehyde in dust form has been suggested but needs thorough trial in forest nurseries under various conditions before it can be recommended.

(4) *Carbon disulfide emulsion:* — Carbon disulfide is used for the control of animal parasites and insects, particularly Japanese beetle larvae, but does not control fungous diseases unless it is combined with formaldehyde. The emulsion is prepared from water, rosin-fish oil soap, carbon disulfide, and other substances. These constituents are agitated in special mixers. The stock solution obtained is diluted with water. Commercial formaldehyde is added to this emulsion in case the control of fungous parasites is desired. The emulsion is applied by means of pails or hose. The composition of the emulsion and its rate of application vary with conditions and satisfactory disinfection requires the supervision of an expert (Fleming and Baker, 1935).

Pure carbon disulfide is highly inflammable and explosive. Prolonged exposure to the gas causes dizziness. The cost of treatments is very high. Carbon disulfide does not satisfactorily control white grubs which are the most destructive pests in the forest nurseries. All of these shortcomings limit the use of carbon disulfide in forest nurseries.

(5) *Chlor-picrin:* — Chlor-picrin is a heavy liquid, made by the interaction of bleaching powder and picric acid (Howard and Stark, 1939). It destroys eelworms and insect parasites, but does not control fungous diseases.

In treating nursery beds, holes are made from 5 to 6 inches deep, and 14 inches apart. Approximately 2.5 ml. or 1/12 oz. of liquid is inserted into the hole by means of a special pipette. The hole is immediately closed by pinching the soil together with a thrusts of the heel. The entire bed is then covered with oil-treated paper, which is tucked down at the edges of the bed to a depth of 3 to 4 inches. After three days the paper is removed, and the bed prepared for seeding. Treatment is extremely dangerous to growing nursery stock.

(6) *Sulfur powder:* — Sulfur powder has been applied extensively in forest nurseries as a means of damping-off control, but has not always proven to be efficient. Nevertheless, sulfur in moderate quantity is desirable on all nursery soils which are less acid than *p*H 6.0. It acts as a preventative against some damping-off fungi by acidifying the soil, and also acts as a fertilizer both directly and by rendering avalaible other soil nutrients. The usual rate of application varies from 100 to 300 pounds per acre depending upon the reaction and texture of the soil. Even this light application must be made well ahead of seeding, as the intermediate products formed in sulfur oxidation are extremely toxic to plants. A thorough incorporation of sulfur powder throughout the surface 8-inch layer of soil is essential.

An addition of sulfur may be advantageously supplemented by a generous application of duff which will speed up the oxidation process. The sulfur most commonly used in forest nurseries is the grade of which 90 per cent will pass through an 80-mesh sieve.

(7) *Aluminum sulphate:* — Recently this salt has been used extensively for acidification of soil and damping-off control (Hartley, 1929). It has proven to be only partly efficient as a fungicide, even when the rate of application on sandy soil was as high as 500 pounds per acre. The repeated application of aluminum sulphate at the biennial rate of 400 pounds per acre on poorly buffered sandy soil led to a general deterioration of the stock in several forest nurseries.

It appears, therefore, that aluminum sulphate may be used only in moderate quantities for deep acidification of soils, especially those of heavy texture, purely as a preventive measure. The amount necessary for acidification of a particular soil is usually found by treating small amounts of soil with different quantities of aluminum sulphate and measuring the resulting *p*H values (Jackson, 1933).

(8) *Lead arsenate:* — Lead arsenate powder has been used for poisoning white grubs. The efficiency of this chemical in reducing the injury is questionable, since cases have been reported in which the seed beds were destroyed by grubs in spite of heavy application of the insecticide. In a quantity exceeding 200 pounds per acre lead arsenate is extremely toxic, especially on strongly acid soils. It causes either death of the seedlings or serious injury to the roots which later become subject to the attack of *Fusarium* and other fungi.

Direct spearing of grubs with a board studded with knitting needles and rototilling are often used now in preference to poison. A three-field rotation system may be of help in reducing grub injury if green manure is planted after the egg-laying season of the beetles.

Use of Organic Remains: — A number of observations in the greenhouse and in several nurseries in the Lake States have indicated that the addition of acid peat and raw humus has a tendency to reduce fungous diseases. This effect may be attributed to a variety of conditions, *e.g.*, increase in soil acidity, buffering action preventing injury to roots by salts in solution, and supply of plant food in the form of humates which may increase the strength of root tissues of germinating seedlings and thus shorten the period of their susceptibility to disease (WILDE and HULL, 1937; TEN HOUTEN, 1939). Moreover, the application of suitable organic remains may increase the number of organisms directly or indirectly responsible for the reduction of parasites (WEINDLING, 1932; ALLEN and HAENSELER, 1935; WAKSMAN, 1937; GARRARD and LOCKHEAD, 1938).

Miscellaneous Means of Parasite Control: — Glacial acetic acid, pyroligneous acid, phosphoric acid, organic and inorganic mercury compounds, zinc salts, copper sulfate, Bordeaux mixture, and numerous other chemicals have been suggested for the control of soil-inhabiting parasites. However, none of these has found extensive use in forest nurseries because of low efficiency, high cost, or deteriorating effect upon the soil. Future investigations may lead to the discovery of chemicals with strong but not lasting toxic effect in soil. Dusting of seeds with a mixture of cadmium oxide and organic mercurials is receiving increased attention (RIKER, GRUENHAGEN, and ROTH, 1943). Treatment of seed beds with boiling water has been tried, but the results were not satisfactory. The addition of charcoal has been advocated as a means of damping-off control, but there is little information available in regard to this method. The covering of seed beds with pure excavated sand previous to seeding gave satisfactory results in some instances (TOUMEY and NEETHLING, 1923).

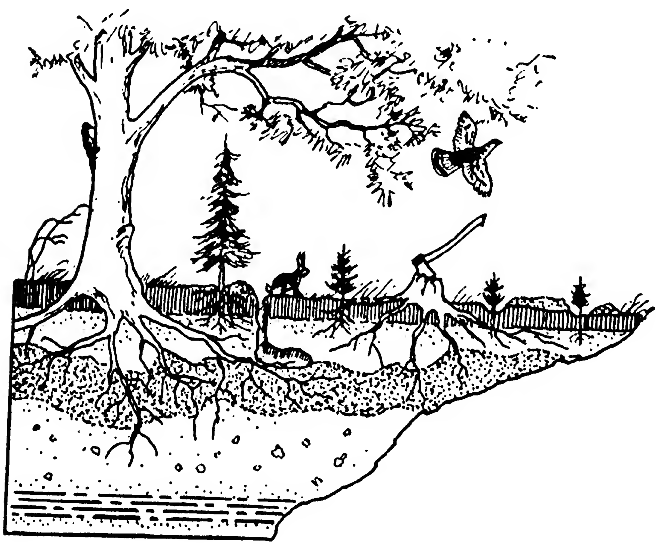
Some foresters avoid disinfecting the soil by abandoning the nursery and selecting a new site as soon as parasites become troublesome. This practice, however, may not always be successful, unless the new nursery is located on recently cleared land. Quite often soils which have been cleared for some time, including soils of acid reaction, are infested with *Pythium, Rhizoctonia,* and other parasites.

Preventive Measures: — In many instances, the control of parasites by toxic chemicals is bought at the price of deterioration of the nursery stock, and the situation is simply a case of the cure being worse than the disease. Fortunately, the disease itself or its degree of virulence is often a direct function of the environment and the condition of the infested plants. Numerous examples from modern practice strongly suggest that the success of the forester's fight against nursery pests may lie less in the search for more efficient means of soil disinfection than in the proper adjustment of ecological conditions, biological relationships, and balanced nutrition. It is especially important to hasten the early growth of plants by suitable fertilization, and so shorten the period of susceptibility of young stock to diseases.

In the light of these conceptions, preventive measures acquire a particular significance. The saying that "an ounce of prevention is worth a pound of cure" may be literally applicable to forest nursery practice. The most important measures preventing the development of parasites may be briefly summarized as follows:

(*1*) Very careful use of materials which encourage the development of parasitic organisms, namely, alkaline organic remains, lime, wood ashes, and commercial fertilizers decreasing the acidity of soil, such as nitrates of soda and calcium cyanamide; (*2*) Maintenance of an acid reaction of nursery soil by applications of suitable acidifying

agents, especially acid peat; (3) Periodic analyses of nursery soil and maintenance of an adequate and balanced supply of available nutrients through the addition of required fertilizers; (4) Regular additions of suitable duff and litter in order to assure an abundance of useful organisms, as well as a supply of available nutrients for their sustenance; (5) Restriction of the use of unbuffered fertilizers or any other unbuffered soluble safts; (6) Maintenance of an adequate content of soil moisture and an adequate degree of soil aeration by carefully regulated artificial watering; (7) Protection of seedlings from extremes of climate by shading, windbreaks, mulching, watering, and other means; (8) Rotation, careful use of green manure crops, sparse seeding, and fall seeding, if possible, or at least early spring seeding; (9) Periodic examination of nursery stock and nursery soil, efficient control of parasites as soon as they appear, weed control, and other forms of sanitation.



REFERENCES

Aaltonen, V. T. 1925. Über den Azeditätsgrad des Waldbodens. Comm. Inst. Forest. Fenn. 9: 26-29.

——— ———. 1937: Über die bodenkundliche Bonitierung der Waldstandorte. Comm. Inst. Forest. Fenn. 25: 5-90.

Aarnio, B., and H. Stremme. 1924: Zur Frage der Bodenbildung und Bodenklassifikation. Agrogeol. Meddelanden 17. Helsingtors.

Afanasiev, J. N. 1927: The classification problem in Russian Soil Science. Russ. Acad. Sci., Pedol. Invest. 5: 1-51.

Agafonoff, M. V. 1930: Sur quelques sols rouges et Binhoa sols de l'Indochine. Soil Res. 2: 184-196.

Albensky, A. 1933: Our achievements in acclimatizing forest tree species. Res. Inst. for Silviculture & Afforestation Bull. 51. Moscow. (In Russian.)

Albert, R. 1912: Bodenuntersuchungen in der Lüneburger Heide. Ztschr. f. Forst- u. Jagdwes. 44: 2, 136, 353, 655. — 1913. *ibid.* 45: 221. — 1914. *ibid.* 46: 82.

——— ———. 1929: Die Bezeichung der Humusformen des Waldbodens. Forstarchiv 5: 103-106.

——— ———. 1938: Untersuchungen über die Verwendbarkeit von Gesteinsabfällen verschiedener Herkunft und Art zur Verbesserung geringwertiger Waldböden. Forstarchiv 14: 229-240.

Albrecht, W. A.. 1941: Calcium saturation and anaerobic bacteria as possible factors in gleization. Soil Sci. 51: 213-215.

Allen, M., and C. M. Haenseler. 1935: Antagonistic action of *Trichoderma* and *Rhizoctonia* and other soil fungi. Phytopath. 25: 244-252.

Alway, F. J., J. Kittredge, Jr., and W. J. Methley. 1933: Composition of the forest floor layers under different forest types on the same soil type. Soil Sci. 36: 387-398.

Anderson, M. L. 1930: A case of "damping off" induced by the use of wood ashes as a manure on seed beds. Scott. For. Jour. 44:7-16.

Arrhenius, O. 1926: Kalkfrage, Bodenreaktion und Pflanzenwachstum. Leipzig.

Association of Official Agricultural Chemists. 1930: Official and tentative methods of analysis. Ed. 3. Washington.

Auten, J. T. 1933: Porosity and water absorption of forest soils. Jour. Agr. Res. 46: 997-1014.

——— ———. 1940: Reconstruction of the hardwood forest soil profile by vegetative covers. Jour. For. 38: 229.

Averell, J. L., and P. C. McGrew. 1929: The reaction of swamp forsest to drainage in northern Minnesota. State Dept. of Drainage and Waters, St. Paul, Minn.

Ayres, Q. C., and D. Scoates. 1939: Land drainage and reclamation. Ed. 2. New York.

Backer, H. P. 1906: The holding and reclamation of sand dunes and sand wastes. Forestry Quart. 4: 282-288.

Bahrt, G. M., and A. E. Hughes. 1937: Soil fertility and experiments on bronzing of citrus. Fla. State Hort. Soc. Proc. 50: 23-28.

Baker, F. S. 1934: Theory and practice of silviculture. New York.

Baldwin, M. 1928: The grey-brown podzolic soils of the eastern United States. Proc. 1st Intern. Cong. Soil Sci. 4: 276-282.

Baldwin, M., C. E. Kellogg, and J. Thorp. 1938: Soil classification. Soils and Men (U. S. D. A. Yearbook) pp. 979-1001. Washington.

Baraney, A. B. 1939: Mycorrhiza. Ann. Rept. Ukr. Res. Inst., Kharkov. (In Russian.)

Baver, L. D. 1940: Soil physics. New York.

Beaman, W. M. 1928: Topographic mapping. U. S. Geol. Surv. Bull. 788.

Bear, F. E. 1929: Theory and practice in the use of fertilizers. New York.

Becker-Dillingen, J. 1937: Die Gelbspitzigkeit der Kiefer, eine Magnesia-Mangelserscheinung. Ernähr. d. Pfl. 33: 1-7.

Belousov, V. I. 1921: A report on an expedition to the Saian Region. Pp. 65-100. Petrograd. (In Russian.)

Bennett, H. H. 1939: Soil Conservation. New York.

Bennett, H. H., and R. V. Allison. 1928: The soils of Cuba. Washington.

Biolley, H. 1920: L'aménagement des forêts par la méthode expérimentale. Paris.

Blanck, E. 1930: Handbuch der Bodenlehre 3: 194-257. Berlin.

Bonner, J. 1937: The role of vitamins in plant development. Bot. Rev. 3: 616-640.

Borggreve, B. 1883: Der Lichtungsbetrieb mit Unterbau. Forstl. Blätter (N. F.).

Bornebusch, C. H. 1930: The fauna of forest soils. Forst. Forsoksv. Danmark 11: 1-224.

——— ———. 1931: Deep investigations of soil. Forstl. Forsoksv. Danmark 13: 1-49. (In Danish.)

Bornebusch, C. H., and S. O. Heiberg. 1935: Proposal for the nomenclature of forest humus layers. Trans. 3rd Intern. Cong. Soil Sci. 3: 259-260.

Bottomley, W. B. 1914: The bacterial treatment of peat. Jour. Roy. Soc. Arts 62: 373-380.

Bouyoucos, G. J. 1927: The hydrometer as a new method for the mechanical analysis of soils. Soil Sci. 23: 343-353.

——— ———. 1929: A new, simple, and rapid method for determining the moisture equivalent of soils. Soil Sci. 27: 233-241.

——— ———. 1940: An electrical resistance method for the continuous measurement of soil moisture under field conditions. Mich. Agr. Exp. Sta. Tech. Bull. 172.

Bowman, I. 1911: Forest physiography. New York.

Boyce, J. S. 1938: Forest pathology. New York.

Braun-Blanquet, J. 1932: Plant sociology. New York.

Bray, W. L. 1915: The development of the vegetation of New York State. N. Y. Sta. Coll. For. Tech. Bull. 3. (Ed. 2. 1930.)

Brenchley, W. E. 1927: Inorganic plant poisons and stimulants. Ed. 2. New York.

Brener, W. H. 1939: Multiple use sprayer for the application of liquid fertilizers, insecticides, and soil disinfectants in forest nurseries. Jour. For. 37: 630.

Brener, W. H., and S. A. Wilde. 1941: The effect of non-legume green manure upon the fertility of forest nursery soils. Jour. For. 39: 478-482.

Briggs, L. J., and J. W. McLane. 1907: The moisture equivalent of soil. U. S. Bur. Soils Bull. 45.

Briggs, L. J., and H. L. Shantz. 1914: Relative water requirements of plants. Jour. Agr. Res. 3: 1-64.

Brockmann-Jerosch, H. 1919: Baumgrenze und Klimacharakter. Zürich.

Bruce, D., and F. X. Schumacher. 1935: Forest mensuration. New York.

Buchanan, H. F. 1807: Journey from Madras, Canara, and Malabar. London.

Buchholz, E. 1930: Der Russische Steppen-Waldbau. Ztschr. f. Forst- u. Jagdwes. 62: 233-241.

Buckman, H. O. 1932: Forest nursery soils problems. Proc. For. Nurserymen's Conf. N. Y. Cons. Dept. pp. 32-36.

Buffault, P. 1936: Aperçu d'ensemble sur la Région Landaise et sa transformation par la forêt. Revue des Eaux et Forêts 64: 273-280; 338-346.

Bühler, A. 1922: Der Waldbau. Ed. 2. Stuttgart.

Bujakowsky, W. 1930: Beitrag zur Bedeutung des Humus für die Nährstoffversorgung unserer Waldbäume. Ztschr. Forst- u. Jagdwes. 62: 257-280.

Burger, H. 1922: Physikalische Eigenschaften der Wald- und Freilandböden. Mitt. Schweiz. Zentralanst. forstl. Versuchswes. Zürich.

——— ———. 1926: Die physikalische Bodenuntersuchung insbesondere die Methoden zur Bestimmung der Luftkapazität. Proc. 4th Intern. Conf. Soil Sci. 2: 150-163.

——— ———. 1931: Holzarten auf verschiedenen Bodenarten. Mitt. Schweiz. Zentralanst. forstl. Versuchswes. 16: 49-128.

——— ———. 1937: Drainage and afforestation. Mitt. Schweiz. Zentralanst. forstl. Versuchswes. 20: 5-81.

Büsgen, M. 1910: Der Kameruner Küstenwald. Ztschr. Forst- u. Jagdwes. 264.

Büsgen, M., and E. Münch. 1929: Structure and life of forest trees. New York.

Cady, J. G. 1938: The role of green manure crops in the maintenance of forest nursery soils fertility. M. S. thesis. University of Wisconsin.

Cajander, A. K. 1909: Über Waldtypen. Acta Forest. Fenn. 1.

——— ———. 1913: Studien über die Moore Finnlands. Acta Forest. Fenn. 2.

——— ———. 1924: Zur Frage der allgemeinen Bedingungen der Kultur ausländischer Gewächse. Mitt. Deutsch. Dendr. Ges. 1.

——— ———. 1926. The theory of forest types. Acta Forest. Fenn. 31.

Chandler, R. F., Jr. 1939: Cation exchange properties of certain forest soils in the Adirondack section. Jour. Agr. Res. 59: 491-505.

Chapman, H. D., and W. P. Kelley. 1930: The determination of the replaceable bases and the base exchange capacity of soils. Soil Sci. 30: 391-406.

Chapman, H. D., and G. F. Liebig, Jr. 1940: Nitrate concentration and ion balance in relation to citrus nutrition. Hilgardia 13: 141-173.

Chapman, H. H. 1931: Forest management. New York.

Chautard, J. 1905: Étude géophysique et géologique sur la Fouta Djallon. Paris.

Chavannes, E. A. 1940: The steep prairies of southern Wisconsin and their invasion by forest. Ph.D. thesis. University of Wisconsin.

Cieslar, J. 1901: Der Sinn der Mycorhizen-Bildung. Centralbl. f. d. Ges. Forstw. 27: 44-45.

Clarke, G. R. 1924: Soil acidity and its relation to the production of nitrate and ammonia in woodland soils. Oxford Forestry Memoirs 2.

Clements, F. E. 1909: Plant formations and forest types. Soc. Am. For. Proc. 4: 50-63.

——— ———. 1916: Plant succession. Carnegie Inst. Wash. Publ. 242.

——— ———. 1920: Plant indicators. Carnegie Inst. Wash. Publ. 290.

Clements, F. E., and V. Shelford. 1939: Bio-ecology. New York.

Clements, J. B. 1938: Trials in Nyasaland of introduced pines. Australian Forestry 3: 21-23.

Cobb, W. B. 1931: Changes in chemical composition produced by the formation of pedalferic soils from different parent materials. Am. Soil Surv. Bull. 12: 87-92.

Coile, T. S. 1933: Soil reaction and forest types in the Duke Forest. Ecology 14: 323-333.

—— ——. 1935: Relation of site index for shortleaf pine to certain physical properties of the soil. Jour. For. 33: 726-730.

—— ——. 1938: Classification of forest sites with special reference to ground vegetation. Jour. For. 36: 1062-1066.

Collings, G. H. 1941: Commercial fertilizers, their sources and use. Ed. 3. Philadelphia.

Cotta, B. 1852: Praktische Geognosie für Land- und Forstwirte und Techniker. Dresden.

Cotta, H. 1809: Systematische Anleitung zur Taxation der Waldungen. Berlin.

Cowles, H. C. 1899: The ecological relations of the vegetation of the Chicago region. Bot. Gaz. 27: 95-116, 167-202, 281-308, 361-391.

Dachnowski, A. P. 1933: Peat deposits in U.S.A. Handbuch der Moorkunde 7: 1-140.

Darwin, C. 1859: The origin of species. London.

—— ——. 1881: Earthworms and vegetable mould. Trans. Geol. Soc. 5: 505.

Deines, G. 1938: Die forstliche Standortslehre. Hannover.

Dengler, A. 1930: Waldbau auf ökologischer Crundlage. Berlin.

Dokturovsky, V. S. 1922: Swamps and peats, their development and composition. Moscow. (In Russian.)

Dokuchaev, V. V. 1879: The chernozem of European Russia. St. Petersburg. (In Russian.)

—— ——. 1899: On the theory of natural zones. St. Petersburg. (In Russian.)

Donahue, R. L. 1936: The relation of soil character as expressed by certain soil types to the choice of land for forestry in the cut-over pine lands of northern Michigan. Am. Soil Surv. Bull. 17: 79-80.

—— ——. 1937: Physical and chemical studies of two contrasting clay forest soils. Jour. For. 35: 16-23.

Drosdoff, M., and E. Truog. 1935: A method for removing and determining the free iron oxide in soil colloids. Jour. Am. Soc. Agron. 27: 213-317.

Eaton, T. H., Jr., and R. F. Chandler, Jr. 1942: The fauna of forest-humus layers in New York. Cornell Univ. Agr. Exp. Sta. Mem. 247.

Eberhard, J. 1922: Der Schirmkeilschlag und die langenbrander Wirtschaft. Forstwiss. Zbl. 41.

Ebermayer, E. 1876: Die gesamte Lehre der Waldstreu. Berlin.

—— ——. 1882: Die naturgesetzlichen Grundlagen des Wald- und Ackerbaues. Berlin.

—— ——. 1900: Einfluss der Wälder auf die Bodenfeuchtigkeit. Stuttgart.

Edin, F. G. 1928: Guide for draining swamp forests. Lulea. (In Swedish.)

Ehrenberg, P. 1933: Wie soll man heut Kampost herstellen und anwenden? Ztschr. Pflanzenernähr., Düng. u. Bodenk. T. B. 12: 193-202.

Emeis, C. 1875: Waldbauliehe Forschungen und Betrachtungen. Berlin.

—— ——. 1908: Die Ursachen der Ortsteinbildung. Heidekultur Verein f. Schlesw.-Holst. 9, 20.

Emerson, F. V. 1920: Agricultural geology. New York. (Rev. ed. by J. E. Smith, 1928.)

Erdmann, F. 1930: Altern, Erkranken, Entarten des Waldbodens. Silva 253.

Falck, R. 1923: Erweitere Denkschrift über die Bedeutung der Fadenpilze für Natzbarmachung der Abfallstoffe zur Baumernährung im Walde, und über die Möglichkeit einer nachtraglichen pilzlichen Aufschiliessung des Trockentorfs. Mykol. Untersuch. u. Ber. 2: 38-72.

Fallou, F. A. 1862: Pedologie oder allgemeine und besondere Bodenkunde. Dresden.

Feher, D. 1933: Untersuchungen über die Mikrobiologie des Waldbodens. Berlin.

Feustel, T. C., and H. G. Byers. 1930: The physical and chemical characteristics of certain American peat profiles. U.S.D.A. Tech. Bull. 214.

—— ——, —— ——. 1936: The comparative moisture-absorbing and moisture-retaining capacity of peat and soil in mixtures. Proc. Soil Sci. Soc. Am. 1: 323-325.

Fisher, E. A. 1923: Some factors affecting the evaporation of water from soil. Jour. Agr. Sci. 13: 121-143.

Fleming, W. E., and F. E. Baker. 1935: The use of carbon disulphide against the Japanese beetle. U.S.D.A. Tech. Bull. 478.

Florov, N. 1925: Über die Degradierung des Tschernosioms in den Waldsteppen. Anuarul. Inst. Geol. al Romaniei 11.

Francé, R. H. 1921: Das Edaphon. Stuttgart.

Frank, A. B. 1885: Über die auf Wurzelsymbiose beruhende Ernährung gewisser Bäume durch unterirdische Pilze. Ber. d. deut. bot. Ges. 3: 128-145.

—— ——. 1887: Über neue Mycorhiza-Formen. Ber. d. deut. bot. Ges. 5:305-409.

Frank, E. 1927: Über Bodenazidität im Walde. Freiburg.

Fraser, G. K. 1933: Studies of Scottish moorlands in relation to tree growth. Forestry Comm. Bull. 15. London.

Fred, E. B. 1916: Relation of green manure to the failure of certain seedlings. Jour. Agr. Res. 25: 1161-1176.

Fred, E. B., I. L. Baldwin, and E. McCoy. 1932: Root nodule bacteria and leguminous plants. Univ. Wis. Stud. Sci. 5.

Fred, E. B., and S. A. Waksman. 1928: Laboratory manual of general microbiology. New York.

Frosterus, B. 1914: Beitrag zur Kenntnis der Bodenbildung. Int. Mitt. Bodenk. 4: 105-137.

Galdieri, A. 1913: L'origine della terra rossa. Bull. Soc. Nat. Am. R. Scuola d'Agric. Portici.

Galloway, H. M. 1940: Origin and properties of alkaline raw humus. Soil Sci. 49: 295-301.

Garrard, E. H., and A. G. Lockhead. 1938: Relationships between soil microorganisms and soil-borne plant pathogens. Sci. Agric. 18: 719-737.

Gasparrini, G. 1856: Ricerche sulla natura dei succiatori la escrezione delle radici. Naples.

Gast, P. R. 1937*a*: Contrasts between the soil profiles developed under pines and under hardwoods. Jour. For. 25: 11-16.

—— ——. 1937*b*: Studies on the development of conifers in raw humus. III. The growth of Scots pine seedlings in pot cultures of different soils under varied radiation intensities. Medd. Statens Skogsförs. 29: 587-682.

Gayer, K. 1878: Der Waldbau. Berlin.

Gedroiz, K. K. 1912: Colloidal chemistry in relation to the problems of soil science. Zhur. Opit. Agr. 13. (In Russian.)

—— ——. 1918: Contributions to our knowledge of the absorptive capacity of soils. Zhur. Opit. Agr. 19: 269-322. (In Russian.)

—— ——. 1926: Chemische Bodenanalyse. Berlin.

—— ——. 1929: Der absorbierenden Bodenkomplex und die absorbierten Bodenkationen als Grundlage der genetischen Bodenklassifikation. Dresden-Leipzig.

Gerhardt, P. 1900: Handbuch des deutschen Dünenbaues. Berlin.

Giersberg, F. 1901: Kunstliche Düngung im forstlichen Betriebe. Berlin.

Giesecke, F. 1930: Tropische und subtropische Humus- und Bleicherdebildungen. Blancks Handbuch der Bodenlehre 4: 184-224.

Girard, H. 1868: Grundlagen der Bodenkunde für Land- und Forstwirte. Halle.

Glinka, K. D. 1908: Soil Science. St. Petersburg. (In Russian.)—German transl. 1914. Die Typen der Bodenbildung. Berlin.—English transl. 1935. The great soil groups of the world and their development. (Ed. 2.)

—— ——. 1931. Soil Science. Ed. 4. (In Russian.)

Glømme, H. 1932: Investigations of the ammonia and nitrate production in different types of humus and factors influencing these processes. Norges Landbrukshøiskole 1: 298-325.

Gola, G. 1910: Saggio di una teoria osmotica dell'edafismo. Ann. Bot. 8.

Gorshenin, K. P. 1924: The influence of forest plantations on the chemical and morphological properties of chernozem. Pochvovedenie 19: 41-78. (In Russian.)

Graham, S. A. 1929: Principles of forest entomology. New York.

Grandeau, L. 1879: Cours de d'agricole de l'école forestière. Nancy.

Grebe, C. 1852: Forstliche Gebirgskunde, Bodenkunde, und Klimalehre. Wien.

—— ——. 1886. Gebirgskunde, Bodenkunde und Klimalehre in ihrer Anwendung auf Forstwirtschaft. Berlin.

Greeley, W. B. 1920: Forest policy in France: The control of sand dunes and mountain torrents. Am. Forestry 26: 3-9.

Grosskopf, W. 1935: Stoffliche und morphologische Untersuchungen forstlichungünstiger Humusformen. Thar. Forstl. Jahrb. 86: 48-111.

Gutorovich, I. I. 1897: Notes of a northern forester. Lesnoi Zhur. 27. (In Russian.)

Guttenberg, A. 1911: Die Forstbetriebseinrichtung. Ed. 2. Wien.

Hackmann, G. 1929: Stand der Humusforschung. Forstarchiv 5: 321-326.

Haig, I. T. 1929: Colloidal content and related soil factors as indicators of site quality. Yale Univ. School of For. Bull. 24.

Hall, A. D., and F. J. Plymen. 1902: The determination of available plant food in soils by the use of weak acid solvents. Trans. Chem. Soc. 81: 117-144.

Hansson, A. 1936: Micro-fauna; the cause of damping off. Rept. For. Off. New Zealand Railways.

Harper, H. J. 1924*a*: The accurate determination of nitrates in soils. Phenoldisulfonic method. Indus. & Eng. Chem. 16: 180-183.

—— ——. 1924*b*: The determination of ammonia in soil. Soil Sci. 18: 409-418.

Harrassowitz, H. 1926: Laterit. Berlin.

—— ——. 1930: Boden der tropischen Regionen. Blancks Handbuch der Bodenlehre 3: 362-436.

Hartig, R. 1886: Über symbiotische Erscheinungen im Pflanzenleben. Bot. Centralbl. 25: 350-352.

—— ——. 1888: Die pflanzlichen Wurzelparasiten. Centralbl. f. Bakt. u. Parasit. I. Abt. 3: 19-22, 58-60, 91-93, 118-120.

—— ——. 1894: Text book of the diseases of trees. London.

Hartley, C. 1921: Damping-off in forest nurseries. U.S.D.A. Bull. 934.

—— ——. 1929: Forest tree seedlings kept from damping-off by aluminum sulphate. U.S.D.A. Yearbook 1928: 332-334.

Hartmann, F. 1925: Untersuchungen zur Azidität markischer Kiefern und Buchenstandorte unter Berücksichtigung typischer Standortsgewächse als Weiser. Ztschr. Forst- u. Jagdwes. 57: 321.

Hatch, A. B. 1936: The role of mycorrhizae in afforestation. Jour. For. 34: 22-29.

—— ——. 1937: The physical basis of mycotrophy in *Pinus*. Black Rock For. Bull. 6.

Hausrath, H. 1911: Pflanzengeographische Wandlungen der deutschen Landschaft. Stuttgart.

Hawley, R. C. 1929: The practice of silviculture. New York.

Hawley, R. C., and C. A. Coover. 1934: Have you a sufficient knowledge concerning the soil in your forest? Jour. For. 32: 437-440.

Heath, O. V. S. 1929: A method of water control for sand cultures. Ann. Bot. 43: 71-79.

Heiberg, S. O. 1933: Factors influencing the choice of species in artificial reforestation. Jour. For. 31: 311-317.

—— ——. 1941: Silvicultural significance of mull and mor. Proc. Soil Sci. Soc. Am. 6: 405-408.

Heiberg, S. O., and R. F. Chandler, Jr. 1941: A revised nomenclature of forest humus layers for the northeastern United States. Soil Sci. 32: 87-99.

Heimburger, C. C. 1934: Forest-type studies in the Adirondack region. Cornell Univ. Agr. Exp. Sta. Mem. 105.

Helbir, M. 1906: Über Düngung im forstlichen Betriebe. Neudamm.

Hellwig, H. 1934: Lupinenunterbau. Forstwiss. Centralbl. 56: 14-18.

Henry, E. 1903: Les forêts de plaine et les eaux souterraines. Revue des eaux et forêts 42: 161-167, 193-201.

—— ——. 1907: Les sols forestiers. Ann. Sci. Agr. 1: 251-418; 2: 1-315. Paris.

Herbert, P. A. 1926: Fertilizing the forest nursery. Mich. Agr. Exp. Sta. Quart. Bull. 8: 188-192.

—— ——. 1936: Society affairs. Feb. issue, Bull. Soc. Am. Foresters.

Hesselman, H. 1910: On the oxygen content of water and its influence on the development of bogs and forest growth. Meddel. Statens Skogsförs. 7: 91-125. (In Swedish.)

—— ——. 1916-1917: Studies of nitrate-formation in soils. Medd. Statens Skogsförs. 13-14: 297-527. (In Swedish.)

—— ——. 1926: Studien über die Humusdecke des Nadelwaldes, ihre Eigenschaften und deren Abhängigkeit vom Waldbau. Medd. Statens Skogsförs. 22: 169-552.

—— ——. 1928: Versumpfung, Rohhumus und Waldbau in Nordschweden. Forstwiss. Zbl. 50: 509-526.

Heusohn, R. 1929: Praktische Kulturvorschläge für Kippen, Bruchfelder, Dünen, und Ödländer. Neudamm.

Heyer, K. 1860: Lehrbuch der forstlichen Bodenkunde und Klimatologie. Erlangen.

Heyward, F., and R. M. Barnette. 1934. Effect of frequent fires on the chemical composition of forest soils in the longleaf pine region. Fla. Agr. Exp. Sta. Bull. 265.

Hilf, H. H. 1938: Die Düngung mit Basalt-Abfällen. Forstarchiv 14: 93-101.

Hilgard, E. W. 1892: The relation of soils to climate. U.S.D.A. Meteor. Bur. Bull. 2.

—— ——. 1906: Soils. New York. (Ed. 3. 1914.)

Hissink, D. J. 1922: Beitrag zur Kenntnis der Adsorptionsvorgänge im Boden. Intern. Mitt. f. Bodenk. 12: 81-172.

Hitchcock, A. E. 1928: Effect of peat moss and sand on rooting response and cuttings. Contrib. Boyce Thompson Inst. 1: 439.

Hopkins, C. G. 1910: Soil fertility and permanent agriculture. Boston.

Hosley, N. W. 1936: Norway spruce in the northeastern United States: a study of existing plantations. Harvard For. Bull. 19.

Hough, A. F. 1942: Soils in a virgin hemlock-beech forest of the northern Allegheny Plateau. Soil Sci. 54: 335-341.

How, J. E. 1940: The mycorrhizal relations of larch. I. A study of *Boletus elegans* Schum. in pure culture. Ann. Bot. 4: 135-150.

Howard, A., and Y. D. Wad. 1931: The waste products of agriculture. London.

Howard, F. L., and F. L. Stark, Jr. 1939: Chlor-picrin soil fumigation. Seed World 45:8.

Hundeshagen, J .C. 1830: Die Bodenkunde in land- und forstwirtschaftlicher Beziehung. (Lehrbuch der land- und forstwirtschaftlichen Naturkunde III.) Tübingen.

Hutchinson, H. B., and E. H. Richards. 1921: Artificial farmyard manure. Jour. Min. Agr. 28. London.

Ilvessalo, Y. 1923: Ein Beitrag zur Frage der Korrelation zwischen den Eigenschaften des Bodens und dem Zuwachs des Waldbestandes. Acta Forest. Fenn. 25.

—— ——. 1926: Über die Anbaumöglichkeit ausländischer Holzarten. Mitt. d. deutsch dendr. Ges. 1.

Imperial Bureau of Soil Science. 1932: Laterite and laterite soils. Tech. Commun. 24.

—— ——. 1934: Soil, vegetation and climate. Tech. Publ. 29.

Ivashkevitch, B. A. 1916: Forests of eastern Manchuria. Izvest. Imper. Lesn. Inst. 30: 163-232. (In Russian.)

Jackson, L. W. R. 1933: Effect of sulfuric acid and aluminum sulfate, as used for the control of damping-off of conifers, on soil *p*H. Phytopath. 23: 18.

Jakuschkin, I. V. 1913: On nitrate formation from peat. Ann. Inst. Agron. Moscow 19: 401-414. (In Russian.)

Jamison, V. C. 1942: Structure of some organic soils and soil mixtures as shown by means of *p*F moisture studies. Jour. Am. Soc. Agron. 34: 393-404.

Jenny, H. 1929: Klima und Klimabodentypen in Europa und in den Vereinigten Staaten von Nordamerika. Soil Res. 1: 139-189.

—— ——. 1930: Hochgebirgsböden. Blancks Handbuch der Bodenlehre. 3: 96-118.

—— ——. 1941: Factors of soil formation. A system of quantitative pedology. New York.

Jensen, H. L. 1929: On the influence of C/N ratios of organic materials on mineralization of N. Jour. Agr. Sci. 19: 71-82.

Joffe, J. S. 1936: Pedology. New Brunswick, N. J.

Johnson, J. 1914: The control of damping-off in plant beds. Wis. Agr. Exp. Sta. Res. Bull. 31.

Juncker, F. 1930: Spruce soil problems in practical forestry. Dansk Skov. Tidsskr. 15: 37-84. (In Danish.)

Kaisler, V. 1921: Control of torrential streams. Techn. Prův. Praha. (In Czech.)

Kamiensky, F. 1881: Die Vegetationsorganen der *Monotropa Hypopitys* L. Bot. Ztng. 39: 458-461.

Kappen, H. 1929: Die Bodenazidität. Berlin.

Kassatkin, V. G., and A. A. Krassiuk. 1917: Instructions for field investigations of soils. Petrograd. (In Russian.)

Kautz, H. 1912: Schutzwald. Forst- und wasserwirtschaftliche Gedanken. Berlin.

Keen, B. A. 1931: The physical properties of the soil. New York.

KELLOGG, C. E. 1936: Development and significance of the great soil groups of the United States. U.S.D.A. Misc. Publ. 229.
——. 1937: Soil Survey Manual. U.S.D.A. Misc. Publ. 274.
KERN, E. 1926a: Erosion control: gullies, their stabilizing, afforestation and terracing. Moscow Coll. of Forestry. Ed. 7. (In Russian.)
——. 1926b: Foreign trees, their peculiarities and significance in forestry. U.S.S.R. Inst. Appl. Bot. (In Russian.)
KING, F. H. 1926: Farmers of forty centuries, or permanent agriculture in China, Korea, and Japan. London.
KITTREDGE, J., JR. 1928: The use of soil surveys in forestry. Proc. 1st Intern. Cong. Soil Sci. 4: 562-565.
KLAGES, K. H. W. 1942: Ecological crop geography. New York.
KLIKA, J. 1929: Forest types in relation to forest ecological research. Sbor. Ces. Akad. Zem. 4A: 229-284. (In Czech.)
KLIMAN, S. 1937: The importance of ferrous iron in plants and soils. Proc. Soil Sci. Soc. Am. 2: 385-392.
KNOX, G. D. 1915: The spirit of the soil. London.
KOBRANOFF, N. P. 1930: Examination of forest plantations. Trudy po lesn. opit. delu 8. Leningrad. (In Russian.)
KOCH, A. 1914: Über die Einwirkung des Laub- und Nadelwaldes auf den Boden. Zbl. Bakt. 2: 570.
KODERLE, J. K. 1865: Die Grundsätze der künstlichen Düngung im Forstkulturwesen. Wien.
KOEPPEN, W., and A. WEGENER. 1924: Die Klimate der geologischen Vorzeit. Berlin.
KÖNIG, J., J. HASENBAUMER, and T. KLEBERG. 1927: Einfluss des Waldhumus auf Boden und Wachstum des Waldes. Veröff. landw. Kammer, Westfalen.
KOPECKÝ, J. 1928: Soil Science (agrophysical part). Min. Zem. Č. S. R., Praha. (In Czech.)
KOPITKE, J. C. 1941: The effect of potash salts upon the hardening of coniferous seedlings. Jour. For. 39: 555-558.
KOROLEFF, A. 1935: Fundamental cause of our failure in forestry and the remedy. Rept. For. Res. Conf., Nat. Res. Counc. Canada, Ottawa: 1-10.
KORZHINSKY, S. 1891: The northern limits of the chernozem region in European Russia from the geobotanical and pedological standpoint. Univ. Kazan, Trudy Ob. Est. 6: 1-204. (In Russian.)
KOSSOVICH, P. 1911: Principles of soil science. St. Petersburg. (In Russian.)
KOTILAINEN, M. J. 1928: Untersuchungen über die Beziehungen zwischen der Pflanzendecke der Moore und der Beschaffenheit, besonders der Torfbodens. Wiss. Veröffentl. Finn. Moorkulturver. 7.
KRASIUK, A. A. 1931: Survey of soils. Moscow. (In Russian.)
KRAUSS, G. 1911: Boden und Klima auf kleinstem Raum. Jena.
KRAUSS, G., and W. GROSSKOPF. 1928: Methode und Beispiele für den regionalen Vergleich der Humusauflage. Thar. Forstl. Jahrb. 79: 325-342.
KRAVKOV, S. P. 1912: Investigations on the role of the dead vegetation layer in soil development. Mater. Izuch. Russ. Pochv. 21: 1-170; 22: 1-98. (In Russian.)
KROODSMA, R. F. 1937: The permanent fixation of sand dunes in Michigan. Jour. For. 35: 365-371.
KRUEDENER, A. VON. 1903: An attempt to group the ground cover in relation to site. Les. Zhur. 33: 1430-1468. (In Russian.)
——. 1916: Principles of forest type classification. Mat. po Izuch. Russ. Lesa 3, 4, and 5. Petrograd. (In Russian.)
——. 1926: Waldtypen als kleinste Landschaftseinheiten bzw. Mikrolandschaftstypen. Petermanns Mitt. 72: 150-158.
——. 1927: Waldtypen, Klassifikation und ihre volkwirtschaftliche Bedeutung. Neudamm.
——. 1934a: Zur Frage der mehrstöckigen Böden. Deutsche Forschung 116-133.
——. 1934b: Forstliche Standortsanzeiger. Ed. 2. München.
KRUMM, J. K. 1941: The composition and effects of fertilizer composts in forest nurseries. M. S. thesis. University of Wisconsin.
KÜHNERT, E. 1930: Kunstdünger im Forstbetriebe. Ztschr. Düng. u. Bodenk. 9B: 389-392.
KVAPIL, K., and A. NEMEC. 1925: Beiträge zur Frage des Einflusses reiner Fichten- und Buchenbestände sowie durch beide Holzarten gebildeter Mischbestände auf einige Eigenschaften des Waldbodens. Ztschr. Forst- u. Jagdwes. 57: 193-231.

LACROIX, A. 1913: Les latérites de la Guinée. Nouv. Arch. du Museum d'Hist. Nat., Paris, 5: 255-358.
LANG, R. 1914: Die klimatische Bildungsbedingungen des Laterits. Chemie der Erde Bd. 1. Jena.
——. 1915. Rohhumus- und Bleicherdebildung im Schwarzwald und in den Tropen. Jahresb. d. Ver. f. vaterl. Naturk. in Württ. 71: 115-123.
——. 1920: Verwitterung und Bodenbildung. Stuttgart.
——. 1934: Erfordert der gute Waldstandort nährstoffreichen Boden? Allg. Forst- u. Jagdztng. 110: 73-79.
——. 1935: Zur Gliederung der Formen des Humus. Proc. 3rd Intern. Cong. Soil Sci. 1: 368-373.
LEBEDEV, A. F. 1906: Humus-calcareous soils and their transformation into podzols. Zhur. opit. agr. 7. (In Russian.)
——. 1928: The movement of ground and soil waters. Proc. 1st Intern. Cong. Soil Sci. 1: 454-494.
LEHOTSKY, K. 1941: Sand dune fixation in Michigan. Jour. For. 39: 998-1004.

LEININGEN, W. Graf ZU. 1908: Ueber Humusablagerungen in den Kalkalpen. Ztschr. Forst- und Landwirt. 6:529.—1909: *ibid.* 7:160-173, 249-273.
——— ———. 1917: Entstehung und Eigenschaften der Roterde. Intern. Mitt. f. Bodenk. 7: 39-65, 177.
——— ———. 1922: Über Waldtypen. Centbl. ges. Forstw. 48:154-164.
——— ———. 1931: Forstwirtschaftliche Bodenbearbeitung, Düngung, und Einwirkung der Waldvegetation auf den Boden. Blancks Handbuch der Bodenlehre 9: 348-496.
LEOPOLD, A. 1933: Game management. New York.
LEVCHENKO, F. I. 1930: Gray soils of the forest steppe in the European part of the U. S. S. R. Pochvovedenie 25: 49-72. (In Russian.)
LIVINGSTON, B. E., and F. SHREVE. 1921: The distribution of vegetation in the United States as related to climatic conditions. Carnegie Inst. Wash. Publ. 284.
LIVINGSTON, L. F., and A. E. WACKERMAN. 1927: Swamp drainage for forestry. Agr. Eng., no. 4.
LOEW, O. 1920: Influence of calcium-magnesium ratio on the growth of plants. Jour. Landw. 68: 225-233.
LOGVINOVA, Z. B. 1929: Peat compost as a fertilizer. Trans. Sci. Inst. Fertil. 56. Moscow. (In Russian.)
LONGWELL, C. R., A. KNOPF, R. F. FLINT, C. SCHUCHERT, and C. O. DUNBAR. 1937: Outlines of geology. New York.
LORENZ, N. VON. 1908: Zur Bekämpfung des Ortsteins. Mitt. forstl. Versuchsanst. Mariabrunn.
LUKKALA, O. J. 1928: Experience gained in moor draining by the Finnish State Forest Service and lines along which research work for moor draining should proceed. Silva Fennica no. 8. (In Finnish.)
LUNDBERG, G. 1926: Handbook for forest drainage. Ed. 2. Stockholm. (In Swedish.)
LUNDEGÅRDH, H. 1931: Environment and plant development. London.
LUNT, H. A. 1937: Forest lysimeter studies under red pine. Conn. Agr. Exp. Sta. Bull. 394.
——— ———. 1938: The use of fertilizer in the coniferous nursery with special reference to *Pinus resinosa.* Conn. Agr. Exp. Sta. Bull. 416.
LUTZ, H. J. 1934: Ecological relations in the pitch pine plains of southern New Jersey. Yale Univ. School of Forestry Bull. 38.
——— ———. 1940: Disturbance of forest soil resulting from the uprooting of trees. Yale Univ. School of Forestry Bull. 45.
LUTZ, H. J., J. B. ELY, and S. LITTLE, JR. 1937: The influence of soil profile horizons on root distribution of white pine (*P. Strobus* L.). Yale Univ. School of Forestry Bull. 44.
LUZE, P. DE. 1927: The drainage of forests. Jour. For. Suisse, no. 5.
LYON, T. L., and H. O. BUCKMAN. 1943: The nature and properties of soils. Ed. 4. New York.

MAGISTAD, O. C. 1925: The aluminum content of the soil solution and its relation to soil reaction and plant growth. Soil Sci. 20: 181-225.
MAKRINOV, I. A., and M. L. STEPANOVA. 1930: The biochemistry and biodynamics of the decomposition of peat. II. Symbiosis of cellulose-decomposing and nitrogen-fixing bacteria in the anaerobic decomposition of peat. Arkh. Biol. Nauk 30: 293. (In Russian.)
MALCHEVSKAIA, N. I. 1933: The microbiological characteristics of certain types of forest soils. Pochvovedenie 28: 229-239. (In Russian.)
MALEIEV, V. P. 1933: Theoretical basis of acclimatization. Leningrad. (In Russian.)
MALMSTRÖM, C. 1928: Drainage of peat soils for forestry purposes. Medd. Statens Skogsförs. 24. (In Swedish.)
MANNS, T. F., and J. M. GOHEEN. 1916: A preliminary report on muck humus as a fertilizer and carrier of beneficial soil bacteria. Dela. Agr. Exp. Sta. Bull. 115.
MANTEUFFEL, V. 1874: Die Hügelpflanzung der Laub- und Nadelhölzer. Ed. 4. Leipzig.
MAŘAN, B. 1938: Influence of profile stratification on the productivity of forest soils. Lesniká Práce 17: 161-173. (In Czech.)
MARBUT, C. F. 1928: A scheme for soil classification. Proc. 1st Intern. Cong. Soil Sci. 4: 1-31.
——— ———. 1935: The soils of the United States. Atlas of Amer. Agric. 3.
——— ———. 1936: Introduction to *Pedology,* by J. S. JOFFE. New Brunswick, N. J.
MATHIEU, A. 1878: Météorologie comparée agricole et forestière. Paris.
MATTHEWS, D. M. 1935: The management of American forests. New York.
MATTHEWS, I. 1935: The zinc sulfate treatment for mottle leaf of citrus trees in Sundays River Valley. Citrus Grower 41: 30-32.
MATTSON, S. 1931: The laws of soil colloidal behavior. V. Ion adsorption and exchange. Soil Sci. 31: 311-331.
——— ———. 1933: The laws of soil colloidal behavior. XI. Electrodialysis in relation to soil processes. Soil Sci. 36: 149-163.
MAXIMOV, N. A. 1938: Plant physiology. New York.
MAYR, H. 1890: Die Waldungen von Nordamerika. Berlin.
——— ———. 1906: Fremdländische Wald- und Parkbäume. Berlin.
——— ———. 1909: Waldbau auf naturgesetzlicher Grundlage. Berlin. (Ed. 2, 1925.)
MAZÉ, P. 1915: Détermination des éléments minéraux rares nécessaires au développement du maïs. Comptes Rend. Acad. Sci. Paris 160: 211-214.
MCCOMB, A. L. 1938: The relation between mycorrhizae and the development and nutrient absorption of pine seedlings in a prairie nursery. Jour. For. 36: 1148-1153.
MCCOOL, M. M. 1932*a*: Value of peats for mineral soil improvement. Contrib. Boyce Thompson Inst. 4: 245.
——— ———. 1932*b*: Use of peats in composts to increase nitrification and plant growth. Contrib. Boyce Thompson Inst. 4: 257.

McDougall, W. B. 1914: On the mycorrhizae of forest trees. Amer. Jour. Bot. 1: 51-74.

McQuilkin, W. E. 1935. Root development of pitch pine, with some comparative observations on shortleaf pine. Jour. Agr. Res. 51: 983-1016.

Meinecke, Th. 1927: Aufforstung des nordwestdeutschen Heidegebietes. Neudamm.

Mejstřík, V., V. Vrbenský, and S. Wilde. 1929: A study of the influence of group-selective cutting upon the reaction and physical properties of soil. Zem. Archiv 20: 1-8. (In Czech.)

Melin, E. 1917: Studies on northern bog-lands with special reference to their forest vegetation after drainage. Norrländskt. Handbibliotek. Akad. Avhandl., Uppsala. (In Swedish.)

——— ———. 1925: Untersuchungen über die Bedeutung der Baummykorhiza. Jena.

——— ———. 1930: Biological decomposition of some types of litter from North American forests. Ecology 11: 72-101.

Merriam, C. H. 1898: Life zones and crop zones of the United States. U.S.D.A., Bur. Biol. Surv. Bull. 10.

Metcalf, C. L., and W. P. Flint. 1939: Destructive and useful insects, their habits and control. Ed. 2. New York.

Meyer, A. 1926: Über einige Zusammenhänge zwischen Klima und Boden in Europa. Chemie der Erde 2: 209-347.

Meyer, L. 1933: Die Düngerwirkung von "Nettolin", einem technisch aus Hochmoortorf hergestellten neuen Humusdünger. Ztschr. Pfl-ernähr. Düng. u. Bodenk. 12B: 262-281.

Miklaszewski, S. 1922: Contribution à la connaissance des sols Rendzina. Comptes Rend. de la Conf. Extraordinaire Géologique à Prague 312.

Millar, C. E. 1932: The use of aerial photographs in Michigan land economic survey. Am. Soil Surv. Bull. 13: 82-86.

Miller, C. F. 1918: Inorganic composition of a peat and of the plant from which it was formed. Jour. Agr. Res. 13: 605-609.

Miller, E. C. 1938: Plant physiology. Ed. 2. New York.

Miller, F. J. 1938: The influence of mycorrhizae on the growth of shortleaf pine seedlings. Jour. For. 36: 526-527.

Minssen, H. 1913: Beiträge zur Kenntnis typischer Torfarten. Jour. Landw. 44: 269-330.

Mirov, N. T. 1935: Two centuries of afforestation and shelterbelt planting on the Russian steppes. Jour. For. 33: 971-973.

Mitchell, H. L. 1939: The growth and nutrition of white pine (*Pinus Strobus* L.) seedlings in cultures with varying nitrogen, phosphorus, potassium, and calcium. Black Rock For. Bull. 9.

Mitchell, H. L., and R. F. Chandler, Jr. 1939: The nitrogen nutrition and growth of certain deciduous trees of northeastern United States. Black Rock For. Bull. 11.

Mitchell, H. L., R. F. Finn, and R. O. Rosendahl. 1937: The relation between mycorrhizae and the growth and nutrient absorption of coniferous seedlings in nursery beds. Black Rock For. Papers 1: 58-73.

Mitscherlich, E. A. 1909: Das Gesetz des Minimums und das Gesetz des abnehmenden Bodenertrags. Land. Jahrb. 38: 527-532.

——— ———. 1923: Bodenkunde für Land- und Forstwirte. Ed. 4. Berlin.

——— ———. 1924: Die Bestimmung des Düngerbedürfnisses des Bodens. Berlin.

Möller, A. 1922: Der Dauerwaldgedanke. Sein Sinn und seine Bedeutung. Berlin.

Monroy, J. A. von. 1921: Dünenaufforstung. Forstwiss. Zbl. 470.

Morgan, M. F. 1941: Chemical soil diagnosis by the universal soil testing system. Conn. Agr. Exp. Sta. Bull. 450.

Morgan, M. F., and H. A. Lunt. 1931: The role of organic matter in the classification of forest soils. Jour. Am. Soc. Agron. 23: 1059-1060.—1932. *ibid.* 24: 655-662.

Morozov, G. F. 1905: Forest types. St. Petersburg. (In Russian.)

——— ———. 1912: Forest science. St. Petersburg. (In Russian.) — German translation, 1928. Die Lehre vom Walde. Neudamm.

——— ———. 1930: Forest types. Moscow. (In Russian.)

Moser, F. 1933: The calcium-magnesium ratio in soils and its relation to plant growth. Jour. Am. Soc. Agron. 25: 365-377.

Müller, J. 1936: Forest types of the Jizera Mountains. Lesnická Práce 15: 478-523. (In Czech.)

Müller, P. E. 1878, 1884: Studies of forest humus. Tidskr. Skovbrug 3: 1-124; 7: 1-232. (In Danish.) — German translation, 1887. Studien über die natürlichen Humusformen. Berlin.

——— ———. 1886: Bemerkungen über die Mycorhiza der Buche. Bot. Centralbl. 26: 22-26.

Multamäki, S. E. 1920: On the swamps of Finland and their afforestation. Acta Forest. Fenn. 16. (In Finnish.)

Murgoci, G. M. 1909: Die Bodenzonen Rumäniens. I. Conf. Intern. Agrogeol. Budapest.

Nechleba, A. 1923: Forest protection. Vys. Šk. lesn. inž. Praha. (In Czech.)

Němec, A. 1928: Untersuchungen über die Humifizierung. Ztschr. Forest- u. Jagdwes. 7-8.

——— ———. 1932: Über den Chlorgehalt des Bodens und die Wirkung von chlorgehältigen Kalisalzen. Forstarchiv 13: 1-5.

——— ———. 1935: Versuche über die Wirkung der Gründüngung auf das Wachstum der Verschulpflanzen in den Waldbaumschulen. Forstwiss. Centralbl. 57: 221-228.

——— ———. 1939: The influence of manuring with compost upon the growth of spruce in nurseries. Lesnická Práce 18: 148-156. (In Czech.)

Němec, A., and S. Borisov. 1938: Chemical properties of a cultivated forest soil. Sbor. Česk. Akad. Zem. 13:435-445. (In Czech.)

NĚMEC, A., and K. KVAPIL. 1923: Soil reaction in relation to biochemical characteristics of forest soil. Sbor. vyz. úst. zem. 2. (In Czech.)

——. 1924. Sur l'intensité de l'assimilation de l'azote atmospherique par les sols forestiers. Bull. Soc. Chim. Biol. 6: 515.

——. 1925: Studien über einige physikalische Eigenschaften der Waldböden. Ztschr. Forst- u. Jagdwes. 57: 540.

NĚMEC, A., and B. MAŘAN. 1936-1938: The influence of cultivation and the use of field crops upon the properties of a forest soil. Sborn. Čes. Akad. Zem. 11:157-175; 12:90-96, 398-407; 13: 178-190. (In Czech.)

NEUBAUER, H., and W. SCHNEIDER. 1923: Die Nahrstoffaufnahme der Keimpflanzen und ihre Anwendung auf die Bestimmung des Nahrstoffgehalts der Böden. Ztschr. Pflanzenernähr. u. Düng. (A) 2: 329-362.

NEUSTRUEV, S. S. 1927: Genesis of soils. Russ. Pedol. Invest. 3. Acad. Sci. U.S.S.R.

NIDA, S. 1932: The rendzinas of Polessie. Abh. Inst. Bodenk. Pulawy 2: 124-154. (In Polish.)

NIKIFOROFF, C. C. 1931: History of A, B, C horizons. Amer. Soil Surv. Assoc. 12: 67-70.

——. 1942: Soil dynamics. Sigma Xi Quart. 42: 36-50.

NOVÁK, V., and I. ZVORYKIN. 1927: Soil survey of the Adamov's Forest. Brno. (In Czech.)

ODEN, S. 1927: The acidity, buffering capacity, and liming of the soil. Meddel. Centralanst. Forsöksv. Jordbruksområdet 318: 1-88. (In Swedish.)

OLIVEROS, S. 1932: The effect of soil inoculation on the growth of Benquet Pine. Makiling Echo 11: 205-214.

OLSEN, C. 1924: Studies on the hydrogen ion concentration of the soil and its significance to the vegetation, especially to the natural distribution of plants. Comptes rend. des trav. du lab. Carlsberg 15. Copenhagen.

OMELIANSKY, V. L. 1931: Microbiology. Ed. 7. Moscow. (In Russian.)

ORLOV, M. M. 1924: Principles of forest management. Leningrad. (In Russian.)

OTOTZKY, P. 1905: Ground water, its origin, behavior and distribution. Vol. 1-2. Trudy opit. lesn. St. Petersburg. (In Russian.)

OUDIN, A. 1938: Soil science and its significance from a forestry point of view. Revue des Eaux et Forêts 76: 703-714.

PACZOSSKY, I. K. 1921: Foundations of phytosociology. Kherson. (In Russian.)

PASSARGE, S. 1929: Morphologie der Erdoberfläche. Berlin.

PEARSON, G. A. 1931: Forest types in the southwest as determined by climate and soil. U.S.D.A. Tech. Bull. 247.

PEARSON, R. S. 1907. The level of subsoil waters with regard to forest. Indian Forester 33: 57-69.

PESSIN, L. J. 1933: Forest associations in the uplands of the lower Gulf Coastal Plain (longleaf pine belt). Ecology 14: 1-14.

PFEIL, W. 1860: Die deutsche Holzzucht begründet auf der Eigentümlichkeit der Forsthölzer und ihr Verhalten zu den verschiedenen Standorte. Tübingen.

PIETERS, A. J. 1927: Green manuring. New York.

PLICE, M. J. 1934: Acidity, antacid buffering, and nutrient content of forest litter in relation to humus and soil. Cornell Univ. Agr. Exp. Sta. Mem. 166.

POGREBNIAK, P. S. 1931: Conditions of forest growth in Podolia. Vasgnil. 10. Kharkov. (In Ukrainian.)

POHLE, R. R. 1904: Forests of northern Russia. Trudy opit. lesn. 4. (In Russian.)

POLYNOV, B. B. 1916: On the problem of forest vegetation as a factor in soil development. Pochvovedenie 16, 18. (In Russian.)

POST, L. VON. 1921: Types of peat and peat soils. Stockholm. (In Swedish.)

PRIANISCHNIKOFF, D. N. 1923: Die Düngerlehre. Ed. 15. Berlin.

——. 1926: The value of peat as a material for the preparation of peat manure and compost. Trudy Nauch. Inst. Udobr. 34: 72-75. (In Russian.)

PROKHOROV, N. 1906: Black forest. (Geobotanical notes on the prairie-forest region of Russia.) Pochvovedenie 4. (In Russian.)

PRONIN, D. Classification of Kovel swamps on the basis of vegetation. Prace nauk. stow. lakarzy 1. (In Polish.)

PUČICH, J. 1907: Karstbewaldung des österreichisch-illyrischen Küstenlandes. Wien.

RAMANN, E. 1890: Die Waldstreu und ihre Bedeutung für Boden und Wald. Berlin.

——. 1893: Forstliche Bodenkunde und Standortslehre. Berlin.

——. 1911: Bodenkunde. Ed. 3. Berlin.

——. 1918: Bodenbildung und Bodeneinteilung. Berlin. — English translation, 1928. The evolution and classification of soils. Cambridge.

RAMM, S. 1893: Über die Frage der Anwendbarkeit von Düngung im forstlichen Betriebe. Stuttgart.

RATHBUN, A. E. 1922: Root rot of pine seedlings. Phytopath. 12: 213-220.

RAYNER, M. C. 1938: The use of soil or humus inocula in nuseries and plantations. Emp. For. Jour. 17: 236-243.

——. 1939: The mycorrhizal habit in relation to forestry. 3. Organic composts and the growth of young trees. Forestry 13: 19-35.

REBEL, K. 1924: Waldbauliches aus Bayern, 2. Diessen.

REIFENBERG, A. 1929: Die Entstehung der Mediterran-Roterde (Terra Rossa). Kolloidchem. Beih. 5.

REMEZOV, N. P. 1932: Contradictory processes as a basis for genetic soil classification. Pochvovedenie 2: 178-206. (In Russian.)

RETAN, G. A. 1914: Effective fertilizers in nurseries. For. Quart. 12: 34-36.

REXHAUSEN, L. 1920: Über die Bedeutung der ektotrophen Mykorhiza für die höheren Pflanzen. Beitr. Biol. d. Pflanzen 14-15: 19-58.

RICHARDS, L. A., and W. GARDNER. 1936: Tensiometers for measuring the capillary tension of soil water. Jour. Am. Soc. Agron. 28: 352-358.

RIKER, A. J., R. H. GRUENHAGEN, and L. F. ROTH. 1943: Control of damping-off of nursery pine seedlings. Phytopath. 33: 11.

ROBINSON, G. W. 1932: Soils. Ed. 2. London.

ROE, H. B. 1928: Productivity of peat soil as influenced by height of the ground water table. Proc. 1st Intern. Cong. Soil Sci. 3: 637.

ROGERS, W. S. 1933: A soil moisture meter depending on the capillary pull of the soil. Jour. Agr. Sci. 25: 326-343.

ROMELL, L. G. 1922: Soil aeration as an ecological factor. Medd. Statens Skogsförs. 19: 125-360. (In Swedish.)

——— ———. 1932: Mull and duff as biotic equilibria. Soil Sci. 34: 161-188.

——— ———. 1935: An example of myriapods as mull formers. Ecology 16: 67-71.

——— ———. 1939: The ecological problem of mycotrophy. Ecology 20: 163-176.

ROMELL, L. G., and S. O. HEIBERG. 1931: Types of humus layer in the forests of northeastern United States. Ecology 12: 567-608.

ROSENDAHL, R. O. 1942: The effect of mycorrhizal and non-mycorrhizal fungi on the availability of difficulty-soluble potash and phosphate minerals. Proc. Soil Sci. Soc. Amer. 7: 477-479.

——— ———. 1943: Mycorrhizae of forest trees: their nutritional, ecological, and silvicultural importance. Ph.D. thesis. University of Wisconsin.

ROSENDAHL, R. O., and S. A. WILDE. 1942: Occurrence of ectotrophic mycorrhizal fungi in soils of cut-over areas and sand dunes. Bull. Ecol. Soc. Amer. 23: 73.

ROTH, F. 1898: Forestry conditions and interests of Wisconsin. U.S.D.A. Bull. 16.

——— ———. 1914: Forest regulation. Mich. Man. of Forestry. East Lansing.

ROTH, L. F., and A. J. RIKER. 1943: Damping-off of red pine seedlings by *Pythium* and *Rhizoctonia*. Jour. Agr. Res. 67:129-148; 265-285; 417-431.

RÜBEL, E. 1930: Pflanzengesellschaften der Erde. Bern.

RUBNER, K. 1925: Die pflanzengeographischen Grundlagen des Waldbaus. Ed. 2. Neudamm.

——— ———. 1927: Waldtypen und Forstwirtschaft. Silva 15: 381-387.

RUDOLPH, P. O. 1939: Why forest plantations fail. Jour. For. 37: 377-383.

RUSNOV, P. 1915: Ein Düngungsversuch in forstlichen Pflanzengärten. Centralbl. gesam. Forstwiss. 41: 173-179.

RUSSELL, E. J. 1936: Soil conditions and plant growth. Ed. 7. London.

RUSSELL, J. C., L. B. OLMSTEAD, and B. H. HENDRICKSON. 1929: Forms of soil structure. Am. Soil Surv. Assoc. Bull. 9: 120-133.

RUSSELL, M. B., and L. A. RICHARDS. 1938: The determination of soil moisture energy relations by centrifugation. Soil Sci. Soc. Am. Proc. 3: 65-69.

SALISBURY, E. J. 1922: Stratification and hydrogen-ion concentration of the soil in relation to leaching and plant succession with special reference to woodlands. Jour. Ecol. 9: 249-250.

SAMPSON, A. W. 1912: The relation of soil acidity to plant societies. Proc. Soc. Am. For. 7: 51-57.

SAMPSON, H. C. 1930: Advantages and limitations in the use of the distribution of soil types as a basis of mapping the distribution of vegetation types. Proc. Ohio Acad. Sci. 8: 1.

SARAUW, G. 1893: Über die Mykorhizen unserer Waldbäume. Bot. Centralbl. 53:346-355.

SCHANTZ, H. L. 1832: Chemie für Landwirte, Forstmänner und Kameralisten. Göttingen.

SCHEFFER, T. C. 1930: Sterilization of coniferous seed-beds with low-pressure steam. Jour. For. 28: 42-49.

SCHIMPER, A. F. W. 1903: Plant geography upon a physiological basis. Oxford.

SCHLICH, W. 1910: Manual of forestry. Ed. 4. London.

SCHNEIDER, W. 1924: Erfahrungen in der Ödlandsaufforstung. Zeitschr. Forst- u. Jagdwes. 169.

SCHOFIELD, R. K. 1935: The *p*F of the water in soil. Trans. 3rd Intern. Cong. Soil Sci. 2: 37-48.

SCHOLZ, H. F. 1931: Physical properties of the cove soils of the Black Rock Forest. Black Rock For. Bull. 2.

——— ———. 1935: Causes of decadence in the old groves of North Dakota. U.S.D.A. Circ. 344.

SCHOPFER, W. H. 1943: Plants and vitamins. Waltham, Mass.

SCHROEDER, J. VON. 1893: Über die Düngung der Saatkämpe und Pflanzengärten mit spezieller Berücksichtigung des Nahrstoffbedarfes junger Fichten. Thar. Forstl. Jahrb. 43: 129.

SCHWAPPACH, A. 1916: Forstdüngung. Neudamm.

SEE, K. VON. 1921: Beobachtungen an Verwitterungsboden auf Kalksteinen. Ein Beitrag zur Frage der Rendzinaböden. Int. Mitt. f. Bodenk. 2: 85-104.

SEMITS, N. 1934: Die physikalischen Eigenschaften des Bodens einiger Bestandstypen Lettlands. Latvia For. Exp. Sta. Bull. 1: 1-63.

SENSTIUS, M. W. 1930: Studies on weathering and soil formation in tropical high altitudes. Proc. Am. Philos. Soc. 69: 45-97.

SEREX, P., JR. 1917: Plant food materials in the leaves of forest trees. Jour. Am. Chem. Soc. 39: 1286-1296.

SHANTZ, H. L., and C. F. MARBUT. 1923: The vegetation and soils of Africa. New York.

SHANTZ, H. L., and R. ZON. 1924: Natural vegetation. U.S.D.A., Atlas of American Agriculture, 1.

SHAW, B., and L. D. BAVER. 1939: An electrothermal method for following moisture changes of the soil in situ. Soil Sci. Soc. Am. Proc. 4.

SHIRLEY, H. L., and L. T. MEULI. 1939: The influence of soil nutrients on drought resistance of two-year old red pine. Am. Jour. Bot. 26: 355-360.

Shreve, F., M. A. Chrysler, F. H. Blodgett, and F. W. Besley. 1910: The plant life of Maryland. Md. Weather Serv. Spec. Publ. 3.

Sibirtzev, N. M. 1900: Soil science. (Lectures at Novo-Alexandriisky College of Forestry.) St. Petersburg. (In Russian.) — Ed. 3, 1914.

Sigmond, J. 1924: Science of forest habitats. Vys. Škola lesn. inž. Praha. (In Czech.)

—— ——. 1930: Der Waldhumus. Forstarchiv 453.

Silcox, F. A., *et al.* 1935: Possibilities of shelterbelt planting in the Plains region. Rept. Lake States For. Exp. Sta. Washington.

Smirnoff, W. P. 1914: Über die in den Gebirgsgegenden Russlands vorkommenden vertikalen Bodenzonen. Intern. Mitt. Bodenk. 4: 405.

Smith, H. H. 1932: Ethnobotany of the Ojibwe Indians. Bull. Milwaukee Publ. Mus. 4: 327-525.

Snyder, E. F. 1928: Methods for determining the hydrogen-ion concentration of soils. U.S.D.A. Circ. 56. — Rev. ed., 1935.

Sokolovsky, A. 1931: A rational nomenclature of genetic horizons in soils. Ukr. Inst. Soil Res. Bull. 3.

Sorensen, S. P. L. 1909: Enzymstudien II. Biochem. Ztschr. 21.

Spaulding, P. 1908: The treatment of damping-off in coniferous seedlings. U.S.D.A. Bur. Plant Ind. Circ. 4.

Sprengel, K. 1831: Chemie für Landwirte, Forstmänner und Kameralisten. Göttingen.

Springer, G. 1925: Aufforstungsmöglichkeit von Hochmooren in Deutschland und in Schweden. Ztschr. Forst- u. Jagdwes. 105.

Stahl, E. 1900: Der Sinn der Mykorrhizenbildung. Eine vergleichende biologische Studie. Jahrb. f. Wiss. Bot. 34: 539-668.

Stark, V. N. 1930: Methods of investigation of the insect fauna of forest soil. Zashchita Rastenii 6: 763-772. (In Russian.)

Stebutt, A. 1930: Lehrbuch der allgemeinen Bodenkunde. Berlin.

Steven, H. M. 1928: Nursery investigations. Great Brit. For. Comm. Bull. 11.

Stickel, P. W. 1929: Physical characteristics and silvicultural importance of Podzol soil. Ecology 9: 176-187.

Stiny, J. 1908: Berasung und Bebuschung des Ödlandes im Gebirge. Graz.

Stöckli, A. 1938: Why and how should we make compost? Schweiz. Landw. Monatsh. 15: 1-22.

Stoeckeler, J. H. 1940: Effect of fertilizers on survival of seedlings. Lake States Forest Exp. Sta. Tech. Notes No. 162.

Stoeckeler, J. H., and E. Aamodt. 1940: Use of tensiometers in regulating watering in forest nurseries. Plant Phys. 15: 589-607.

Stoeckeler, J. H., and C. H. Bates. 1939: Shelterbelts: the advantages of porous soils for trees. Jour. For. 37: 205-221.

Stoeckeler, J. H., and G. A. Limstrom. 1942: A site classification for reforestation on the national forests of Wisconsin. Jour. For. 40: 308-315.

Stoklasa, J. 1930: Humusbildung in Waldboden. Zbl. Forstwes. 184.

Stoklasa, J., and E. G. Doerell. 1926: Handbuch der biophysikalischen und biochemischen Durchforschung des Bodens. Berlin.

Stone, E. L. 1940: Calcium requirements of some coniferous and deciduous seedlings. M.S. thesis. University of Wisconsin.

Stremme, H. 1915: Laterit und Terra Rossa als illuviale Horizonte humoser Waldböden. Geol. Rundschau 5: 480-499.

—— ——. 1930: Die Braunerde. Blancks Handbuch der Bodenlehre 3:160-182.

Süchting, H. 1925: Der Abbau der organischen Stickstoffverbindungen des Waldhumus durch biologische Vorgänge. Forstwiss. Centralbl. 47: 108-117, 174-188, 264-276.

—— ——. 1928: Die Gründüngung im forstlichen Betriebe. Ztschr. Forst- u. Jagdwes. 1928: 321.

—— ——. 1929*a*: Der Bekämpfung des Humus der Waldboden. Ztschr. forst- u. Jagdwes. 61: 349-363.

—— ——. 1929*b*: Der Kalk als Grundlage der Waldbodenkultur. Berlin.

—— ——. 1939: On the determination for practical purposes of the productivity of forest soils. Forstarchiv 15: 111-122.

Süchting, H., G. John, G. Deines, and G. Maurmann. 1933: Untersuchungen über die Wirkung der Düngung auf Waldböden zugleich Beitrag zur Methodik der Bestimmung der Bodengüte. Mitt. Forstwirtsch. u. Forstwiss. 4: 439-493.

Sukachev, V. 1913: Introduction to the study of plant communities. St. Petersburg. (In Russian.)

—— ——. 1923: Bogs, their formation, development and properties. Ed. 2. Leningrad. (In Russian.)

—— ——. 1930: Guide for the investigation of forest types. Ed. 2. Moscow. (In Russian.)

—— ——. 1932: Die Untersuchungen der Waldtypen des osteuropäischen Flachlandes. Abderhaldens Handb. biol. Arbeitsmeth. 11: 6: 191-250.

Tacke, B. 1930: Die Humusböden der gemässigten Breiten. Blancks Handbuch der Bodenlehre 4: 124-183.

Tamm, O. 1920: Soil studies in the north Swedish coniferous forest. Medd. Stat. Skogsförs. 17: 49-300. (In Swedish.)

—— ——. 1921: On the influence of rock substrata on forest soils. Medd. Stat. Skogsförs. 18: 105-164. (In Swedish.)

—— ——. 1930: Die Bodentypen und ihre forstliche bedeutung. Intern. Cong. For. Exp. Sta. Proc. 1929: 449-453.

—— ——. 1931: Studies of soil types and their relation to moisture in northern Swedish forests. Medd. Stat. Skogsförs. 26: 163-408. (In Swedish.)

TANFILIEV, G. I. 1892: Across the tundras of the Timan Samoyeds. Comm. Russ. Geogr. Soc. 30. (In Russian.)

TANSLEY, A. G., and T. F. CHIPP. 1926: Classification of mature soils according to climatic soil types. (In "Aims and methods in the study of vegetation.") London.

TEN HOUTEN, J. G. 1939: Damping-off diseases of conifers. Utrecht. (In Dutch.)

THIÉRY, E. 1915: Restauration des montagnes, correction des torrents par reboisement. Paris.

THOMAS, E. E., and A. R. C. HAAS. 1928: Injection method as a means of improving chlorotic orange trees. Bot. Gaz. 86: 355-362.

THOMAS, W. 1937: Foliar diagnosis: principles and practice. Plant Phys. 12: 571-599.

THORNE, C. E. 1930: The maintenance of soil fertility. New York.

THORNTON, S. F., S. D. CONNER, and R. R. FRASER. 1934: The use of rapid chemical tests on soils and plants as aids in determining fertilizer needs. Ind. Agr. Exp. Sta. Circ. 204.

THORP, J. 1931: The effects of vegetation and climate upon soil profiles in northern and northwestern Wyoming. Soil Sci. 32: 283-297.

—— ——. 1936: Geography of the soils of China. Nanking.

TILLOTSON, C. R. 1917: Nursery practice in the national forests. U.S.D.A. Bull. 479.

TIURIN, I. V. 1930: Genesis and classification of forest-steppe and forest soils. Pochvovedenie 25: 104-141. (In Russian.)

TKACHENKO, M. E. 1908: The role of the forest in soil development. Izv. Imp. Les. Inst. 18: 1-144. (In Russian.)

—— ——. 1911: Forests of the north. Trudy lesn. opit. del. 25. (In Russian.)

—— ——. 1935: Eliminating metaphysics from forest soil science. Pochvovedenie 30: 481-492. (In Russian.)

TOUMEY, J. W. 1916: Foundations of silviculture upon an ecological basis. New Haven, Conn.

TOUMEY, J. W., and C. F. KORSTIAN. 1928: Foundations of silviculture upon an ecological basis. New York.

—— ——, —— ——. 1931: Seeding and planting in the practice of forestry. New York.

TOUMEY, J. W., and E. J. NEETHLING. 1923: Some effects of cover over coniferous seedbeds in southern New England. Yale Univ. School of Forestry Bull. 9. New Haven.

TRENK, F. B. 1938: Shelterbelts for windblown soils. Univ. Wis. Coll. Agr. Ext. Serv. Circ. 287.

TROUP, R. S. 1928: Silvicultural systems. Oxford.

TRUOG, E. 1918: Soil acidity: its relation to the growth of plants. Soil Sci. 5: 169-195.

—— ——. 1928: How plants feed. Proc. 1st Intern. Cong. Soil Sci. 3: 628-636.

—— ——. 1930: The determination of the readily available phosphorus of soils. Jour. Am. Soc. Agron. 22: 874-882.

—— ——. 1937: Availability of essential soil elements — a relative matter. Proc. Soil Sci. Amer. 1936, 1: 135-142.

—— ——. 1938: A modern conception of soils, fertilizer action, and plant nutrition. Proc. Nat. Fert. Assoc. pp. 66-78.

—— ——. 1940: Instructions for making the Truog soil reaction test and information about soil reaction and liming. Hellige, Inc., New York.

TRUOG, E., and J. SYKORA. 1917: Soil constituents which inhibit the action of plant toxins. Soil Sci. 8: 333-351.

TSCHERMAK, L. 1930: Vorschläge zur Reform der Bezeichungsweise der Humusformen des Waldbodens. Proc. Intern. Cong. For. Exp. Sta. Stockholm, pp. 589-590.

TUBEUF, K. F. VON. 1888: Beiträge zur Kenntnis der Baumkrankheiten. Berlin.

—— ——. 1903: Beiträge zur Mycorhizafrage. II. Über die Ernährung der Nadelbäume durch Mycorhizen. Naturw. Ztschr. Land- u. Forstw. 1: 67-82.

TUMIN, G. M. 1930: The influence of forest strips on the soils of the Kamennaia Steppe. Kam.-Step. Opit. Sta., Voronezh, pp. 1-40. (In Russian.)

TURNER, J. H. 1933: Trees for calcareous soils. Quart. Jour. For. 27: 297-303.

TURNER, L. M. 1938: Some profile characteristics of the pine growing soils of the Coastal Plain region of Arkansas. Ark. Agr. Exp. Sta. Bull. 361.

TURNER, W. I., and V. M. HENRY. 1939: Growing plants in nutrient solutions. New York.

UNITED STATES DEPARTMENT OF AGRICULTURE. 1938: Soils and men. (U.S.D.A. Yearbook.) Washington.

VAGELER, P. 1933: Grundriss der tropischen und subtropischen Bodenkunde. Berlin.

VAGI, I. 1938: Critical observations on Dr. FEHÉR's chemical investigations of forest soils. Erdészeti Kisérletek 40: 54-158. (In Hungarian.)

VATER, H. 1905: Düngunsversuche in Saatkämpen. Thar. Forstl. Jahrb. 55: 116.

—— ——. 1911: Zur Ermittelung des Zulangens der Nahrstoffe im Waldboden. Thar. forstl. Jahrb. 62: 217.

—— ——. 1916: Die Beschreibung des Standortes als Grundlage zur Beurteilung seines Einflusses auf den Pflanzenwuchs. Intern. Mitt. der Bodenk. 6: 159.

—— ——. 1928: Beiträge zur Kenntnis der Humusauflage von Fichte und Kiefer. Mitt. sächs. forstl. Versuchanst. 3: 129-181.

VEATCH, J. O. 1932: Soil maps as a basis for mapping original forest cover. Papers Mich. Acad. Sci. 15: 267-273.

VEIHMEYER, F. J., and A. H. HENDRICKSON. 1931: The moisture equivalent as a measure of the field capacity of soils. Soil Sci. 32: 181-193.

VILENSKY, D. G. 1925: The classification of soils on the basis of analogous series in soil formation. Proc. 1st Intern. Cong. Soil Sci. 1: 224-241.

VILJOEN, J. A., and E. B. FRED. 1924: The effect of different kinds of wood and wood pulp on plant growth. Soil Sci. 17: 199-208.

VOLK, N. J. 1934: The fixation of potash in difficultly available form in soils. Soil Sci. 37: 267-287.

Volk, N. J., and E. Truog. 1934: A rapid chemical method for determining the readily available potash of soils. Jour. Am. Soc. Agron. 26: 537-546.

Vonhausen, W. 1872. Die Düngung der Forstgärten. Allg. Forst- u. Jagdz. 48: 228-231.

Vorobiov, D. V., and P. S. Pogrebniak. 1929: A key to Ukrainian forest types. Trudy z lis. dosv. spr. Ukr. 11. (In Ukrainian.)

Wagner, C. 1907: Die räumliche Ordnung im Walde. Tübingen. — Ed. 4, 1923.

—— ——. 1915: Der Blendersaumschlag und sein System. Ed. 2. Tübingen.

Wahlenberg, W. G. 1929: Modification of western yellow pine root systems by fertilizing the soil at different depths in the nursery. Jour. Agr. Res. 39: 137-146.

Waksman, S. A. 1932: Principles of soil microbiology. Ed. 2. Baltimore.

—— ——. 1937: Soil deterioration and soil conservation from the viewpoint of soil microbiology. Jour. Am. Soc. Agron. 29: 113-122.

—— ——. 1938: Humus — origin, chemical composition, and importance in nature. Baltimore.

Waksman, S. A., and R. L. Starkey. 1931: The soil and the microbe. New York.

Wallihan, E. F. 1939: Use of tensiometers for soil moisture measurement in ecological research. Ecology 20: 403-412.

Wang, F. 1903: Grundriss der Wildbachverbauung. Leipzig.

Ward, H. M. 1899: Symbiosis. Ann. Bot. 13: 549-562.

Waren, H. 1924: Untersuchungen über die botanische Entwicklung der Moore mit Berücksichtigung der chemischen Zusammensetzung des Torfes. Finsk. Moorkulturför. 5.

Warming, E. 1895: Plantesamfund. Grundträk af den ökologiska Plantegeografi. Copenhagen. (In Danish.) — English translation, 1925. Ecology of plants. Ed. 2. Oxford.

Way, J. T. 1850: On the power of soils to absorb manure. Jour. Roy. Agr. Soc. 11: 313-379.

Weaver, J. E. 1919: The ecological relations of roots. Carnegie Inst. Wash. Publ. 286.

Weaver, J. E., and F. E. Clements. 1938: Plant ecology. Ed. 2. New York.

Weindling, R. 1932: *Trichoderma lignorum* as a parasite of other soil fungi. Phytopath. 22: 837.

Weis, F. 1929: Physical and chemical investigations of Danish heath soils (podzols). Det. Kgl. Videnskabernes Sel. Biol. Medd. 7-9. — 1932. *ibid.* 10.

Went, F. 1935: Auxin, the plant growth hormone. Bot. Rev. 1: 162.

Westveld, R. H. 1933: The relation of certain soil characteristics to forest growth and composition in the northern hardwood forest of northern Michigan. Mich. Agr. Exp. Sta. Tech. Bull. 135.

Wherry, E. T. 1927: Divergent soil reaction preferences of related plants. Ecology 8: 197-206.

White, D. P. 1941: Prairie soil as a medium for tree growth. Ecology 22: 309-407.

Whitson, A. R. 1927: Soils of Wisconsin. Wis. Geol. and Nat. Hist. Surv. Bull. 68.

Wiebecke, E. 1920: Der Dauerwald. Stettin.

Wiedemann, E. 1923: Zuwachsrückgang und Wuchsstockungen der Fichte in den sächsischen Staatsforsten. Vorst. Versuchsanst. Thar. — Ed. 2, 1927.

—— ——. 1931: Düngung im Forstbetrieb. (In F. Honcamp, Handbuch der Pflanzenernährung- und Düngerlehre.) Berlin.

—— ——. 1938: Kalkdüngung im Fichtenwalde. Forstarchiv 14: 217-229.

Wiegner, G. 1929: Boden und Bodenbildung in kolloid-chemischer Betrachtung. Ed. 5. Dresden.

Wild, H. 1910: Düngung in den forstlichen Pflanzengärten. Ernähr. d. Pflanz. 63.

Wilde, S. A. 1928: Forest types and forest appraisal. Proc. 6th Cong. Czech. Nat., Phys., & Eng. Praha, 3: 108. (In Czech.)

—— ——. 1929*a*: Principles of an ecological subdivision of forest tracts. Lesnická Práce 8: 5-15; 83-99. (In Czech.)

—— ——. 1929*b*: Physical properties of forest soils. Lesnická Práce 10: 503-514. (In Czech.)

—— ——. 1929*c*: Classification of forest land for the purposes of taxation. Ann. Czech. Acad. Agr. 4: 359-384. (In Czech.)

—— ——. 1931: The designation of horizons of forest soils. Lesnická Práce 10: 161-167. (In Czech.)

—— ——. 1932*a*: Soil survey and forest practice. Am. Soil Surv. Bull. 13: 26-30.

—— ——. 1932*b*: Forest types of Podzol region of U.S.A. Pochvovedenie 27: 5-23. (In Russian.)

—— ——. 1933: The relation of soils and forest vegetation of the Lake States region. Ecology 14: 94-105.

—— ——. 1934: Soil reaction in relation to forestry and its determination by simple tests. Jour. For. 32: 411-418.

—— ——. 1935: The significance of soil texture in forestry and its determination by a rapid field method. Jour. For. 33: 503-508.

—— ——. 1936: Soil Nematodes in forest nurseries. Phytopath. 25: 198-199.

—— ——. 1937*a*: The use of liquid humate fertilizers in forest nurseries. Jour. For. 35: 388-392.

—— ——. 1937*b*: Recent findings pertaining to the use of sulfuric acid for the control of damping-off disease. Jour. For. 35: 1106-1110.

—— ——. 1938: Soil-fertility standards for growing northern conifers in forest nurseries. Jour. Agr. Res. 57: 945-952.

—— ——. 1940*a*: The subdivision of the grey-brown podzolic soils from ecological and silvicultural viewpoints. Proc. Soil Sci. Soc. Am. 5: 336-340.

—— ——. 1940*b*: Classification of gley soils for the purpose of forest management and reforestation. Ecology 21: 34-44.

—— ——. 1942. Rapid colorimetric determination of soil organic matter. Proc. Soil Sci. Soc. Am. 7: 393-394.

Wilde, S. A., and A. R. Albert. 1942: Effect of planting methods on survival and growth of plantations. Jour. For. 40: 560-562.

Wilde, S. A., S. F. Buran, and H. M. Galloway. 1937: Nutrient content and base exchange properties of organic layers of forest soils in the Lake States region. Soil Sci. 44: 231-238.

Wilde, S. A., and H. H. Hull. 1937: Use and function of peat in forest nurseries. Jour. Am. Soc. Agron. 29: 299-313.

Wilde, S. A., and S. Kliman. 1931: Modern trends in nursery practice in the United States. Lesnická Práce 10: 305-315. (In Slovak.)

Wilde, S. A., and J. C. Kopitke. 1940: Base exchange properties of nursery soils and the application of potash fertilizers. Jour. For. 38: 330-332.

Wilde, S. A., and W. E. Patzer. 1940: Soil-fertility standards for growing northern hardwoods in forest nurseries. Jour. Agr. Res. 61: 215-221.

Wilde, S. A., and H. F. Scholz. 1930: The basis for subdividing mountainous forests for the purpose of management. Jour. For. 28: 1104-1109.

—— ——, —— ——. 1934: Subdivision of the Upper Peninsula Experimental Forest on the basis of soils and vegetation. Soil Sci. 38: 383-394.

Wilde, S. A., F. B. Trenk, and A. R. Albert. 1942: Effect of mineral fertilizers, peat, and compost on the growth of red pine plantations. Jour. For. 40: 481-484.

Wilde, S. A., and D. P. White. 1939: Damping-off as a factor in the natural distribution of pine species. Phytopath. 29: 367-369.

Wilde, S. A., and R. Wittenkamp. 1939: The phosphate and potash starvation of forest seedlings as a result of the shallow application of organic matter. Jour. For. 37: 333-335.

—— ——. 1942: Duff briquette fertilizers: their preparation, use, and effect upon the growth of trees and other plants. Jour. Am. Soc. Agron. 34: 736-746.

Wilde, S. A., R. Wittenkamp, E. L. Stone, and H. M. Galloway. 1940: Effect of high rate fertilizer treatments of nursery stock upon its survival and growth in the field. Jour. For. 38: 806-809.

Wiley, H. W. 1931: Principles and practices of agricultural analysis. Ed. 3. Easton, Pa.

Williams, M. B. 1917: Spray irrigation. U.S.D.A. Bull. 495.

Willis, L. G. 1939: Bibliography of literature on the minor elements. Ed. 3. New York.

Wilson, F. G. 1930: Reforestation by private enterprise. Wis. Agr. Exp. Sta. Circ. 239.

Winogradsky, S. 1938: La microbiologie écologique. Ses principes — son procédé. Ann. Inst. Pasteur 61: 731-755.

Wissotzky, G. N. 1902: On growth-stimuli, obstacles, and problems of establishing forests in the steppes of Russia. Trudy 2. s'ezda deiat. selsk. opit. del. (In Russian.)

—— ——. 1905: Gley. Pochvovedenie 7: 291-327. (In Russian.)

—— ——. 1906: An oro-climatic basis for classifying soils. Pochvovedenie 8: 1-17. (In Russian.)

—— ——. 1927: Principles of soil and moisture classification. Bull. Pochv. no. 1-2. (In Russian.)

—— ——. 1930: Forest influences. Leningrad. (In Russian.)

—— ——. 1934: On deep-soil pedology. Pochvovedenie 36: 834-840. (In Russian.)

—— ——. 1938: On the hydrological and meteorological influence of forests. Moscow. (In Russian.)

Wittich, W. 1930: Der Einfluss des Kahlschlages auf den Bodenzustand. Mitt. Forstwirtsch. u. Forstwiss. 1930: 487.

Wityn, J. 1924: Die Hauptphasen des Podsolbildungsprozesses. Riga.

Wohack, F. 1930: Frostschutzwirkung der Kalisalze. Ernähr. der Pflanz. 26: 318-319.

Wollny, E. 1884: Untersuchungen über die kapillare Leitung des Wassers im Boden. Forsch. Geb. Agr.-Phys. 7:269-308.—1885; *ibid.* 8:206-220.

—— ——. 1889: Untersuchungen über den Einfluss der Pflanzendecke und der Beschattung auf die physikalischen Eigenschaften des Bodens. Forsch. Geb. Agr.-Phys. 12: 1-75.

Wright, C. H. 1934: Soil analysis. New York.

Wulff, E. V. 1943: An introduction to historical plant geography. Waltham, Mass.

Young, G. Y., W. C. Davis, and D. H. Latham. 1937: Control of damping-off fungi. Phytopath. 27: 144.

Young, H. E. 1936: A mycorrhiza-forming fungus of *Pinus*. Jour. Austral. Inst. Agr. Sci. 2: 32-34.

Zailer, V., and L. Wilk. 1907: Über den Einfluss der Pflanzenkonstituenten auf die physikalische und chemische Eigenschaften des Torfes. Ztschr. Moorkultur und Torfverwertung, Jahrg. 5: 40-46, 111-128, 197-260.

Zakharov, S. A. 1931: A course in pedology. Ed. 2. Moscow. (In Russian.)

Zavalishin, A. A. 1928: Some observations on the study of soils with a close gley horizon. Leningrad Sel'sko-Khoz. Inst., 45-90. (In Russian.)

Zavalishin, A. A., and A. P. Pronevich. 1928: Report on the geology and soils of Pashe-Kapetsky Forest. Leningrad. (In Russian.)

Zon, R. 1906: Principles involved in determining forest types. Soc. Am. Foresters Proc 1: 179-189.

—— ——. 1927: Forests and water in the light of scientific investigation. U. S. Sen. Doc. 469. Washington.

Zon, R., and J. L. Averell. 1928: The effect of drainage on forest growth. Jour. Agr. Eng. No. 6.

Zvorykin, I. 1929: A contribution to the degradation of rendzina in the Moravian Karst. Proc. Czechoslov. Acad. Agr. 5: 598. (In Czech.)

INDICES

PLATES

AUTHOR INDEX

SUBJECT INDEX

PLATE 1. — Types of substrata that support forest vegetation. — *Left:* Forest soil originated from the weathering of rock and accumulation of organic remains. — *Center top:* Slightly weathered rock outcrops, the most primitive type of forest soil. — *Center bottom:* Submerged forest soil of a bayou. — *Right:* Peat, forest soil composed of pure organic remains (*Photos by U. S. Forest Service and the writer*).

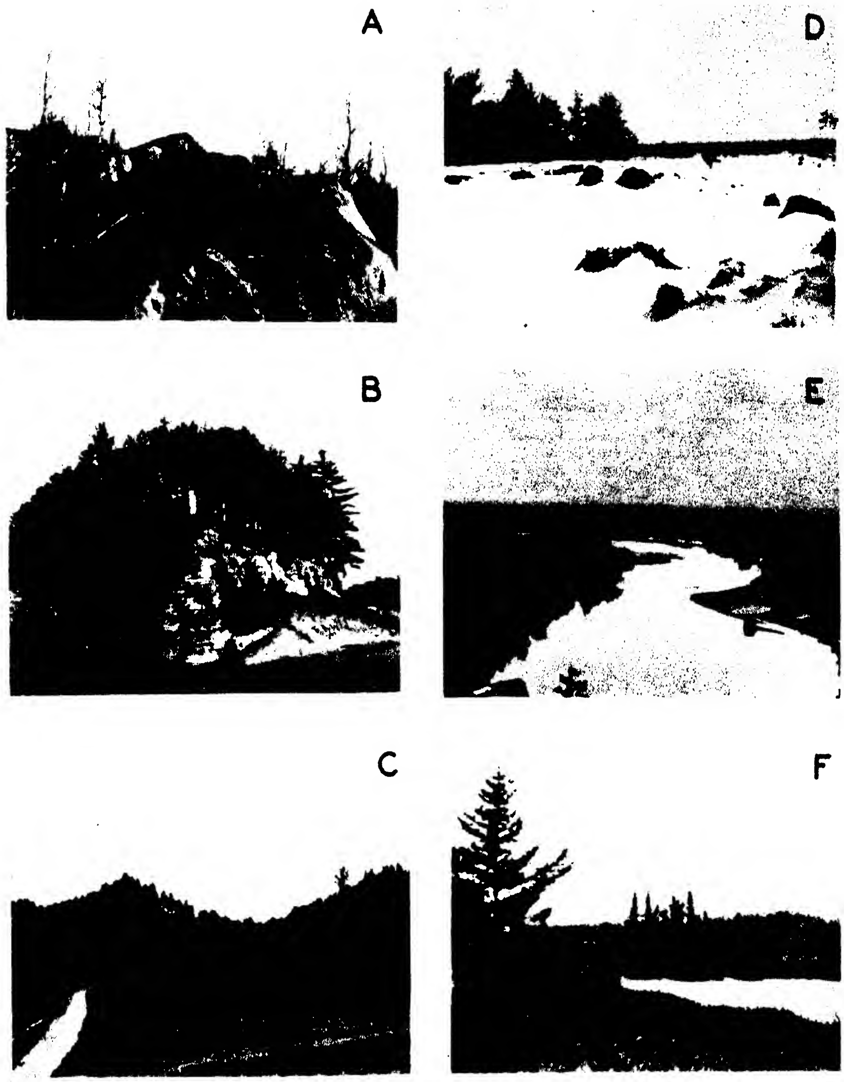


PLATE 2. — Forest soils of different geological origin: (A) Rock outcrops; (B) Residual soil derived from sandstone with talus at the foot of the knoll; (C) Level glacial outwash grading into terminal moraine; (D) Wind-blown sand; (E) Flood plain soils; (F) Cumulose deposits surrounding a shallow glacial lake.

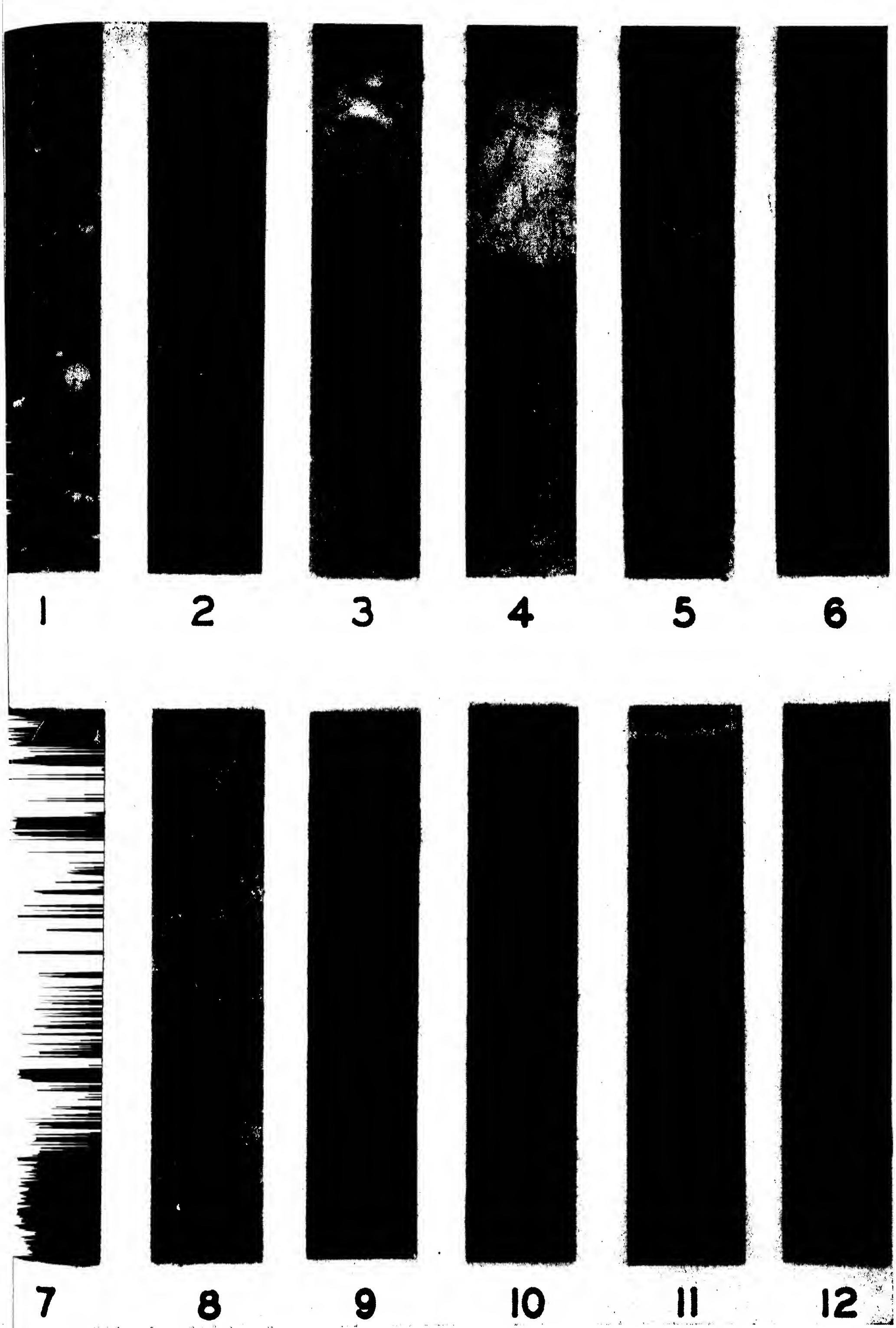


PLATE 3. — Representative profiles of upland forest soils: (1) Weakly podzolized gravelly sand; (2) Weakly podzolized loam; (3) Podzolic sand; (4) Podzol loam; (5) Ortstein podzol of a sandy texture; (6) Calcareous clay podzol; (7) Dark grood loam; (8) Light or leached grood loam; (9) Strongly leached grood loam, approaching podzolic soils; (10) Melanized loam; (11) Melanized lateritic clay; (12) Podzolized lateritic clay.

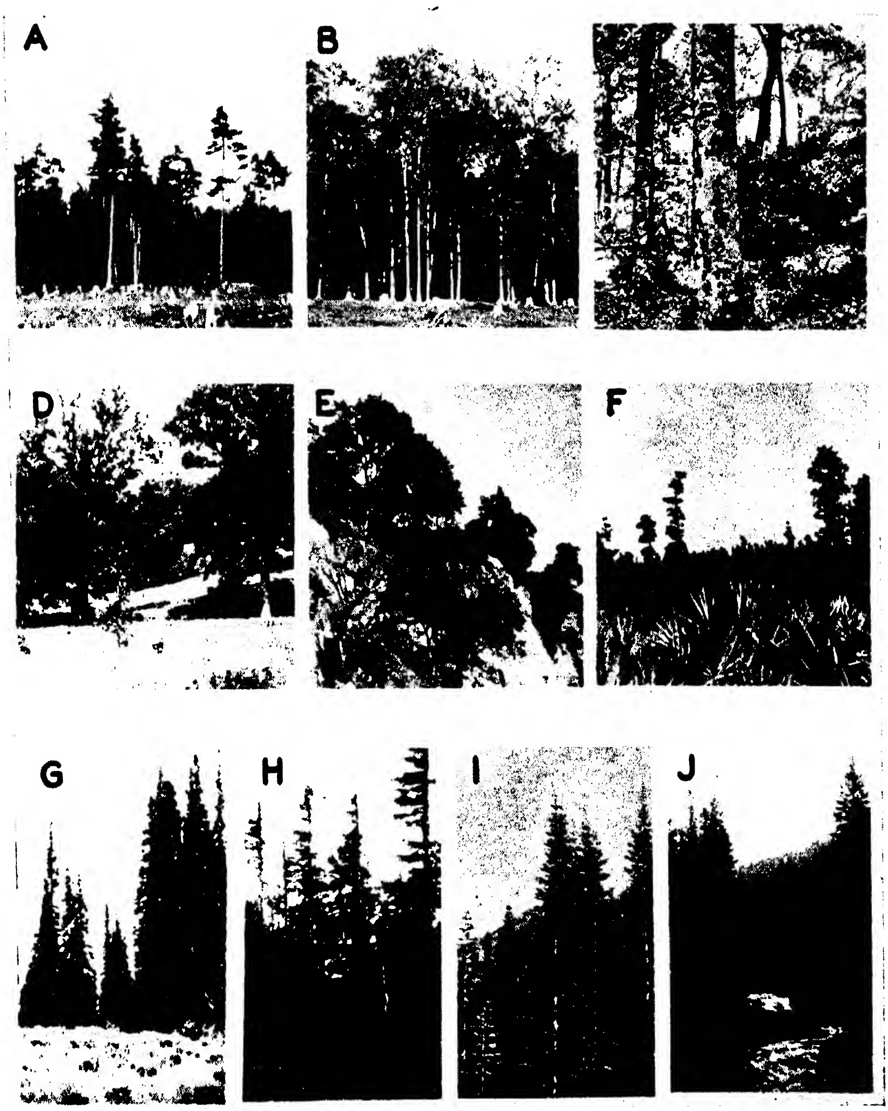
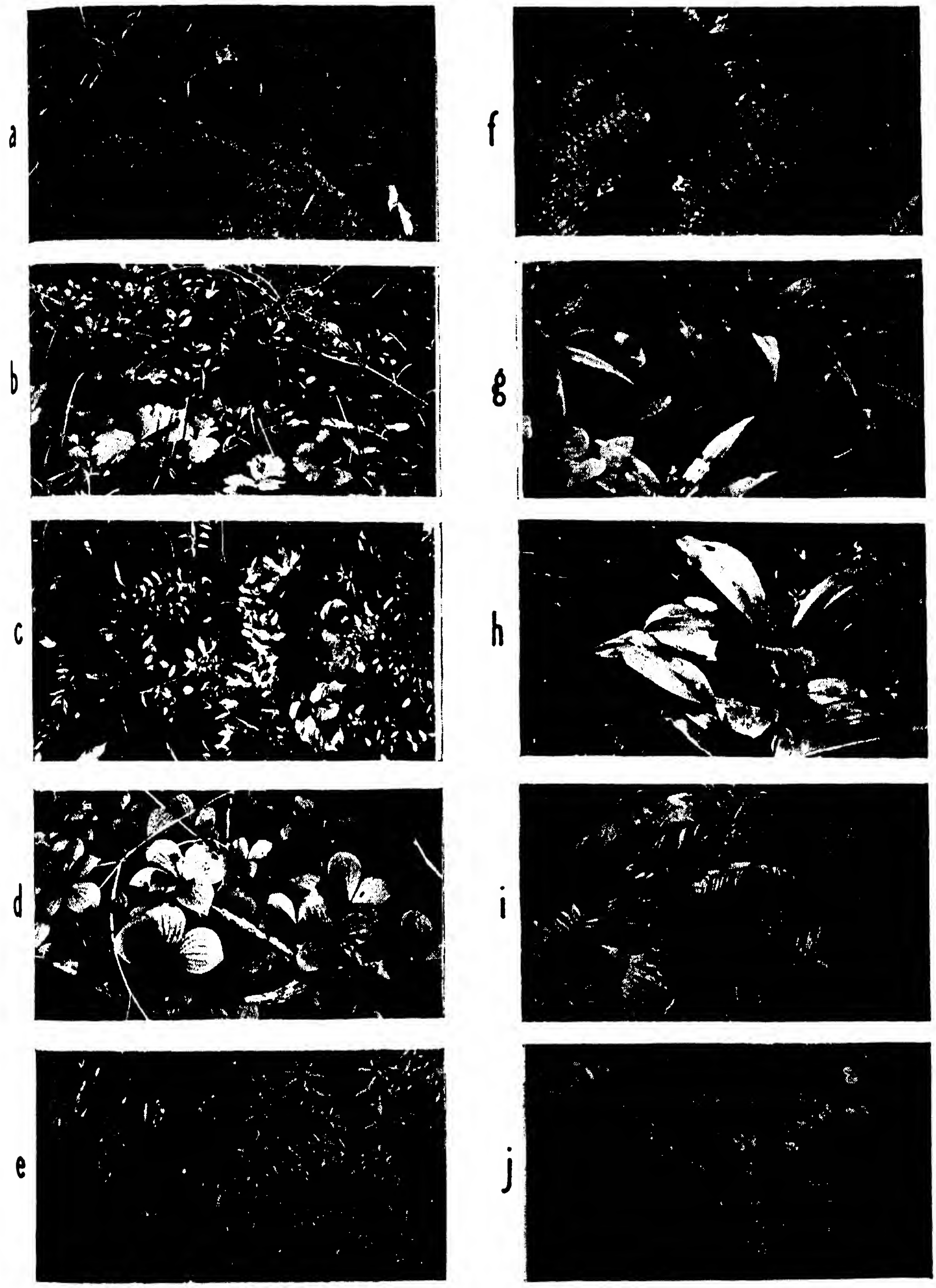
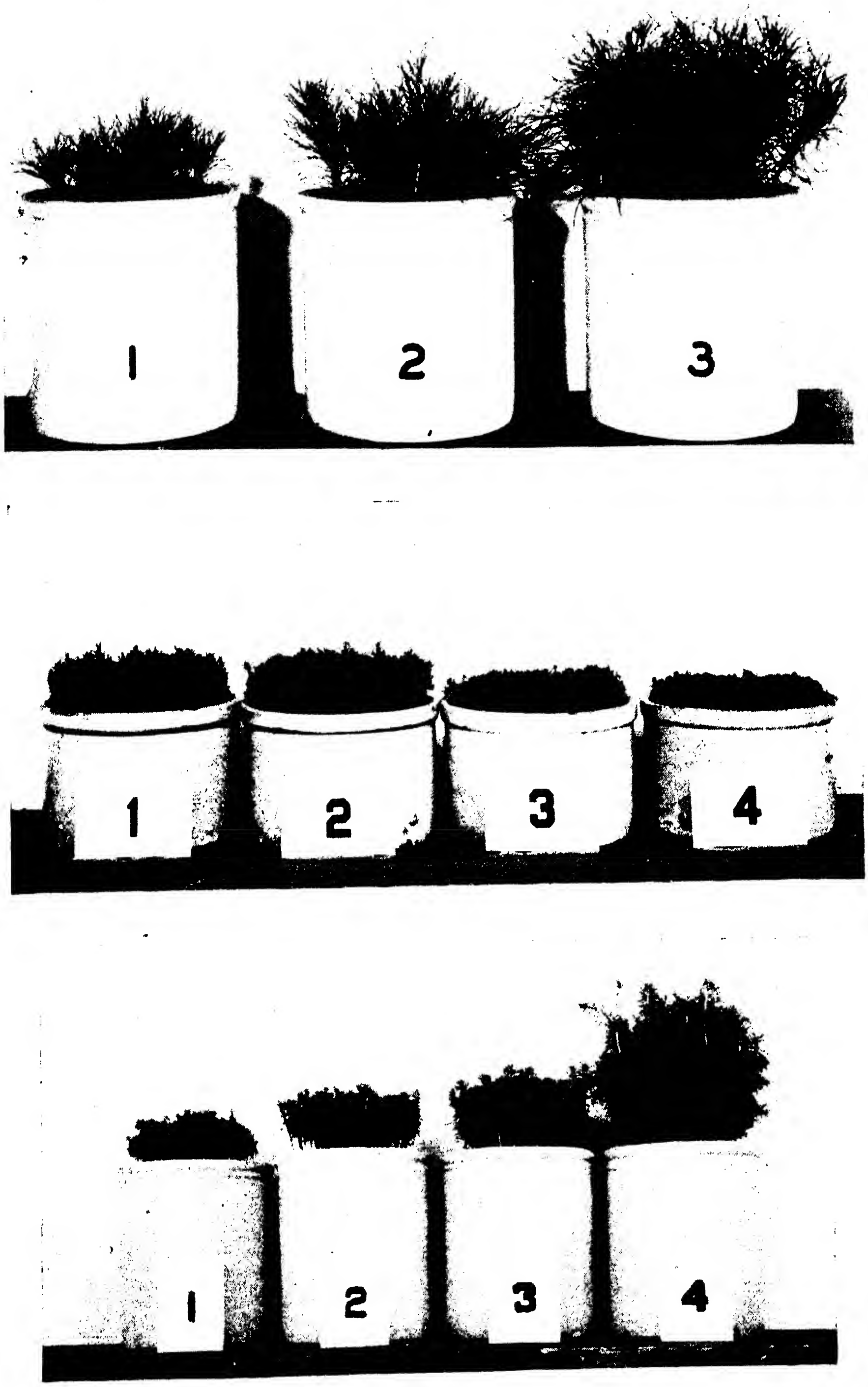


Plate 4. — Characteristic forest cover of the major soil groups: (A) Hardpan podzol — white pine, white spruce and balsam fir; (B) Podzolic loam — maple, basswood, hemlock and balsam fir; (C) Melanized loam — beech and hard maple with associated hardwoods; (D) Grood silt loam — oak and hickory prairie-forest; (E) Degraded rendzina — oak prairie-forest; (F) Podzolized laterite — longleaf pine with understory of palmetto; (G) Sod soil of high mountains — alpine fir; (H) Mountain podzol — Norway spruce and mugho pine; (I) Weakly podzolized mountain soil — Douglas fir; (J) Melanized alluvial soil of mountains — Norway spruce and European fir. (*Photos C, G and I courtesy of U. S. Forest Service*).

PLATE 5. — Characteristic ground cover associations of northern forests: (a) *Cladonia type*, wind-blown sand; (b) *Arctostaphylos type*, melanized outwash sand; (c) *Vaccinium-Gaultheria-Maianthemum type*, podzolic sand; (d) *Vaccinium-Cornus type*, sandy swamp podzol; (e) *Ledum-Chamaedaphne type*, moss peat; (f) *Adiantum - Osmorhiza - Thalictrum type*, melanized loam; (g) *Polygonatum-Uvularia type*, podzolic loam; (h) *Clintonia-Lycopodium type*, loam podzol; (i) *Fern type*, gley loam; (j) *Oxalis-Coptis type*, woody peat.



— Plate 5 —

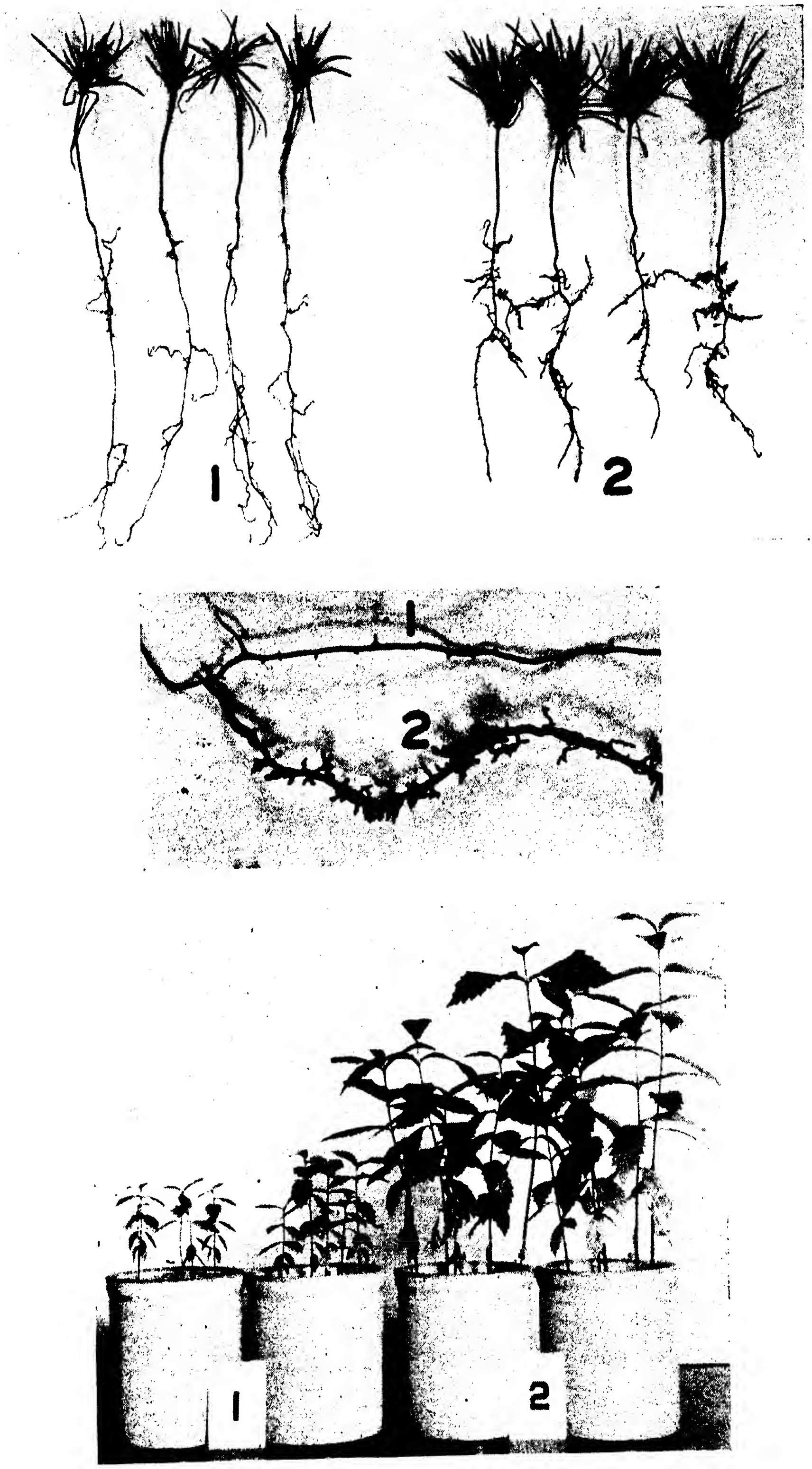


— PLATE 6 —

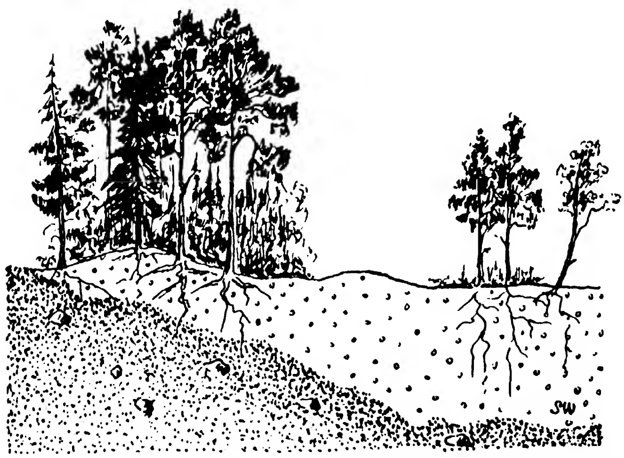
For legend see next page

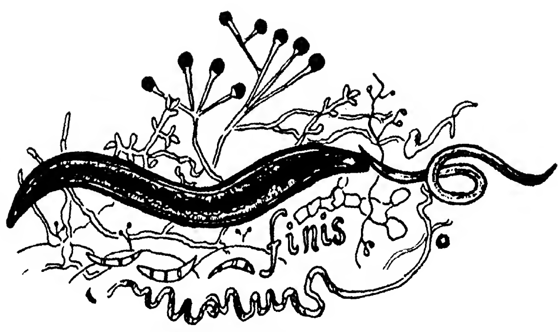
PLATE 6. — Effect of soil fertility factors on the growth of tree seedlings. — *Top:* Two-year-old jack pine raised in a nursery soil of varying nutrient content: (1) Check; (2) Soil supplied with nitrogen, phosphorus and potassium in the forms of acid peat, rock phosphate and feldspar; (3) Similarly treated soil which received an additional light application of ammonium phosphate and potassium nitrate in solution. — *Center:* Six-month-old white spruce seedlings raised in buffered and unbuffered quartz sand cultures: (1) Complete nutrient solution and acid-treated, nearly-neutral bentonite; (2) Unbuffered nutrient solution, a condition that promoted the accumulation of soluble salts in high concentration near the surface, and depressed the growth of trees. — *Bottom:* Growth of two-year-old Norway spruce seedlings on a depleted nursery soil treated with different organic remains at a rate equivalent to 40 tons per acre: (1) Sphagnum moss peat; (2) Carex sedge peat; (3) jack pine duff; (4) hardwood-hemlock duff.

PLATE 7. — Effect of mycorrhizal fungi upon the growth of tree seedlings. — *Top:* Three-month-old red pine seedlings raised in quartz sand cultures: (1) Sterile nutrient solution; (2) Nutrient solution inoculated with pure culture of *Boletus felleus.* — *Center:* Enlarged roots of red pine seedlings: (1) Non-mycorrhizal; (2) Infested with ectotrophic mycorrhizae. — *Bottom:* Seedlings of five-month-old white elm raised in prairie and forest soils of similar texture and fertility: (1) Mycorrhiza-free prairie soil; (2) Mycorrhiza-infested forest soil. (*Photos by* R. O. ROSENDAHL, D. P. WHITE and the writer).



— Plate 7 —


SW


finis